Universitat Politècnica de Catalunya

Experimental Validation of TEAM Concept in PV Grid-Connected Systems

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RINGRAZIAMENTI

Non credo sia possibile ringraziare tutte le persone che in un modo o nell'altro mi hanno aiutato sempre nella mia vita, dentro e fuori dell'ambito universitario per cui spero mi perdonerete se mi limito a ringraziarvi senza menzionare il vostro nome.

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Vi ringrazio infinitamente.

1 INTRODUCTION TO THE THESIS

I am looking for alternatives. The world needs alternatives. Renewable energy is an alternative and a big opportunity for human kind.

We are made of energy, we feed with energy and we live of energy.
About this last point I should specify "especially electric energy"; energy that we produce from different sources and the most widely used one is petroleum which became so important that, to master its domain, many wars have been made for it, often, in name of "human rights".

We need an alternative to this!

Solar energy could be one of the most important alternatives. We live thanks to the sun and as long as the sun lives we live, not only, as long as the sun shines we can collect its energy and live with it. At the beginning is complicated living only of "alternative sources of energy", in fact they are called "alternative" to petroleum for a reason.

The goal for humanity should be improving the amount of energy collected from natural, renewable sources, using and preferring it and so, with time, becoming less dependent from petroleum.

Every country has sun all the year and no wars can be done to modify or improve the amount of sun energy a country can get from the sun. Besides, country that so far have had only lot of sun and nothing else, not even food, might start being self-dependent.

My vision is a pure dream but it would be great if it could be realized, we all would have a better life and in a better society and a cleaner world for us and for the ones coming after us.

I don't have the power to change the destiny of the whole world but there is something I can do, I can choose to prefer working with solar energy and other renewable sources, I can try to find a job who allows me to keep working with that and I can try to convince people to invest money in clean energy and use it. This is what I can do and will do.

The following thesis is about solar energy.

1.1 Efficiency

We want to transform solar energy in electric energy for using it in our houses or to sell it to the electric society. To do that we need a certain number of devices which make the conversion of solar energy into electric energy and then adapt this energy to another form, always electric, which is usable from final users.

Every step of this conversion is characterized in terms of *efficiency*, a parameter that allows us to determinate how much energy we lose along the way with the conversion starting from the primary source till the final one.

To make these systems supplying green energy commercially interesting we must guarantee a certain level of efficiency for the whole process of conversion in a way that “having a solar source” be *economically convenient* and not only *environmental compatible*.

The first task in order to use a photovoltaic (PV) system economically convenient is to build it in a way that it results efficient in terms of energy conversion.

There are studies and criteria for building PV systems and we will recall them, particularly, we will introduce the so called *static* and *dynamic* PV system.
A static PV system is what we can define the base of reference for other systems aiming at the improvement of the efficiency compared with the one of reference.

Therefore the fist task, as we said earlier, is to build an efficient and economically convenient PV system and measure its efficiency; through this parameter we qualify the system itself but we also have a tool of comparison with other systems.

Starting from the configuration of a simple, but efficient, static PV installation, adding features (e.g. sun-tracking system) or using different concepts of design (e.g. dynamic system) we improve, with a certain percentage, the total efficiency of the PV installation.

In this thesis we will explain the criteria to build an efficient grid-connected PV system, then, after introducing concepts on the possible ways of creating dynamic systems, we will experiment and measure the difference between a static PV system and a dynamic PV system based on TEAM concepts.

- We will use a simulated PV generator, inverters and a board of control to replicate in laboratory a working PV system.
- We will also use some databases, representative of the evolution of the solar energy we might get from the sun during some typical days here in Barcelona: consequently we will be experimenting with real data values.
- Finally we will control the board making the system being working in a static way, first, and dynamically, after, and, for each case, we will calculate the efficiency of the system.

The finality of the thesis is to demonstrate how to step from a static system to dynamic system, how much gain in terms of efficiency we can obtain, when and where it is interesting economically and in terms of efficiency to invest into an additional circuitry to modify a static PV system.

Following there is a brief description on how this work has been organized:

- Chapter 2: introduction to grid connected photovoltaic systems;
- Chapter 3: description of static and dynamic systems and criteria for their design;
- Chapter 4: core of the thesis, results of the experimentations made will be shown;
- Chapter 5: description of a possible improvement aimed at increasing even more the global efficiency of the system;
- Chapter 6: conclusions.

2 GRID CONNECTED PHOTOVOLTAIC SYSTEMS

2.1 Introduction

In this chapter we will give a summary description of one of the possible applications of the photovoltaic systems: the grid connected photovoltaic systems.

Some information and some conceptual calls of general nature will be introduced on the components that constitute such systems with the purpose to clarify some points that will be then needed to understand the experiments that will be realized within this thesis.

We will consider working conditions almost ideal, the only parameters of influence will be temperature and irradiance; real conditions parameters like not uniformity of the irradiance or temperature, aging, bypass diode, cells construction asymmetries and so on will not be considered.

2.2 Grid Connected Photovoltaic Systems

In the photovoltaic (PV) installations connected to the electric grid all the produced energy is injected into the grid which can be considered as a ideal load capable of absorbing any available energy. This type of installations is formed from one determined association of solar panels which constitute the so called *photovoltaic generator*, a system made of devices with which it is possible to convert the energy supplied by the sun into electric energy.

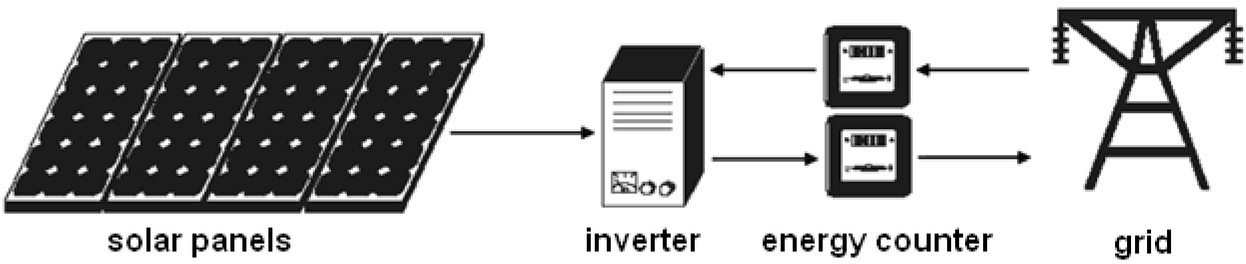

Figure 1.1 shows the general scheme of this type of installations

The energy produced through this type of installations can be commercialized, it is necessary, therefore, that its design aims to the optimization of its efficiency both economical and energetic. With the purpose of realizing solutions made of commercial photovoltaic systems where energy's conversion from solar in electrical is economically attractive, different types of technologies have been developed in terms of photovoltaic panels, conversion devices, architectures of connection for the components of the various subsystems of the photovoltaic plant, etc.

We will see a panning of the various technologies that, opportunely interconnected, allow to realize a photovoltaic system for the injection of electric energy into the electric grid.

A PV system connected to the grid can divide in two great subsystems:

- The PV generator in which the solar energy through the solar radiations, or irradiance, is transformed in DC electric energy.
- The system of conversion of the energy that extract from the previous subsystem DC electric energy and turn it into AC electric energy aiming at maximizing the efficiency and adapting the output in a way suitable to be injected into the grid.

Inside each of these two great subsystems it is possible to identify elements and processes that allow realizing the aforesaid conversions of energy.

2.3 Photovoltaic Generator

The fundamental unity of a PV generator is the solar cell and that can be defined as: "The element that converts the energy produced by the Sun, in form of photons, in electric energy"[1]. A determined number of solar cells mechanically interconnected among them form the solar panel or PV module, being the solar panel the constructive unity of the PV generator. Finally, the photovoltaic generator is itself constituted from the association of solar panels: the different possible associations of groups of solar panels give different possible configurations of the PV generator.

2.3.1 Solar Cell

The solar cell is the fundamental unity of photovoltaic conversion. It is in its inside where the process of transformation happens, therefore, it is the element that fix the maximum value that the output of said transformation can reach and, accordingly, the element that will fix the maximum value of output of the PV generator itself.

The electric current being extracted from the solar cell is the difference between the currents produced by the electric carrier couples electron-hole (e-h) that the incidental light produces inside the cell and the current of the couples e-h that recombine inside the cell itself before being able to be drawn out.

When a solar cell is in short-circuit the voltage to its terminals is zero and the process of recombination exponentially depends from the value of this voltage, the current that can be extracted will be maximum; when the cell is in open circuit, instead, the number of couples recombining is the same of those couples generated, therefore the voltage to the terminals of the cell will be maximum being zero the current.

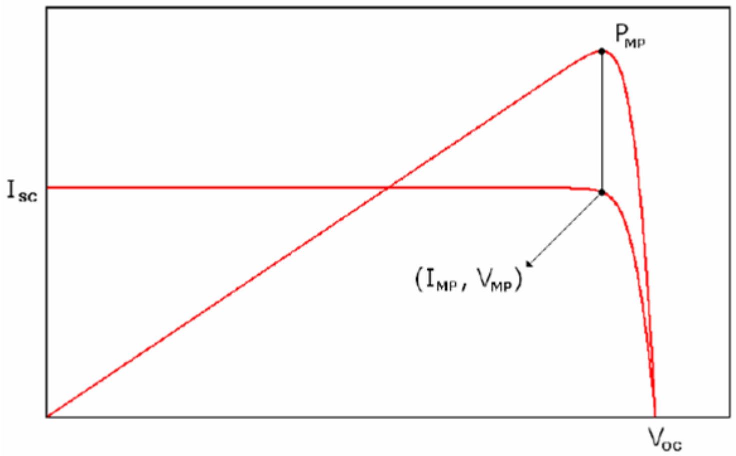

fig. 1.2 characteristic current-voltage and power-voltage of a solar cell

Between these two points of zero electric power there is the point of operation at maximum power of the solar cell that defines its efficiency; it is shown in figure 1.2.

The maximum power that can be produced in one determined solar cell decreases increasing the operating temperature and increases increasing the irradiance to which it is exposed, as it appears in the figure 1.3. If we fix the material with which is built the solar cell, its volume and the value of the irradiance that reaches it, we can affirm that increasing the operating temperature turns into a decreasing output maximum power and then in a less efficient factor of conversion; instead, with the same solar cell but switching temperature and irradiance, we can affirm that the energetic conversion of the solar cell improves increasing the irradiance incident into the cell.

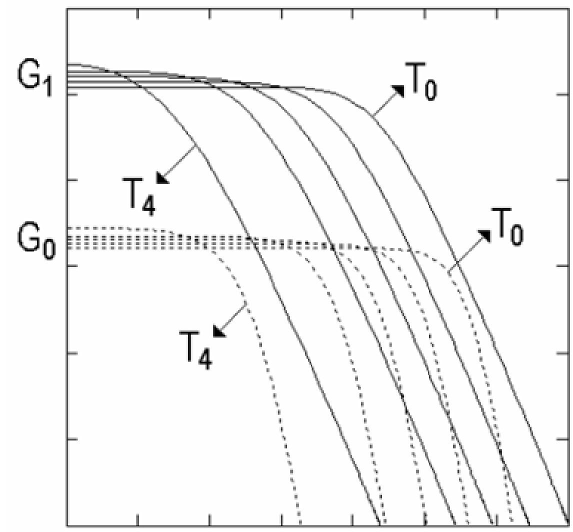

fig. 1.3 Characteristic current-voltage of a solar cell where:
G1>G0 and T4>T3>T2>T1>T0

The preceding curves show that the characteristics of the solar cells:

- Represent a DC power source that varies with irradiance and temperature;
- They show only one point of maximum power which varies with irradiance and temperature.

We confirm that they have not been considered other parameters of influence like:

- The technological factors of manufacture that engrave on the level of irradiance that reaches the active surface of the solar cell and, accordingly they also have influence on the final output of the device.
- The parameters depending on the technology used and the dimensions of the surface contacts (metallic fingers or buried contacts).
- The usage of techniques to modify the texture of the active surface of the solar cell forming microgrooves or inverted pyramids.
- The usage of two or more cells gathered inside the same structure (noted as *tandem cells*) with the purpose to use a greater range of the spectrum of incidental radiation on the device, so that each cell absorbs the energy of a determined range of the spectrum but is transparent to the.

Regarding the inside structure of the materials employed, they are:

- Monocrystalline (commercially predominant and of higher efficiency).
- Multicrystalline, Policrystalline e Microcrystalline.
- Amorphous.

2.3.2 Solar Panel (Module)

A solar cell of silicon supplies a power not superior to 2 Watts under standard conditions of test (STC: it corresponds to an irradiance of 1000 W/m^2, a spectrum AM1.5 and a temperature of 25°C), taking advantage of its characteristic of source of power, we arrange them into a set of solar cells interconnected in series and/or parallel way in order to increase the available power of the whole system so made, as it is represented in the figure 1.4.

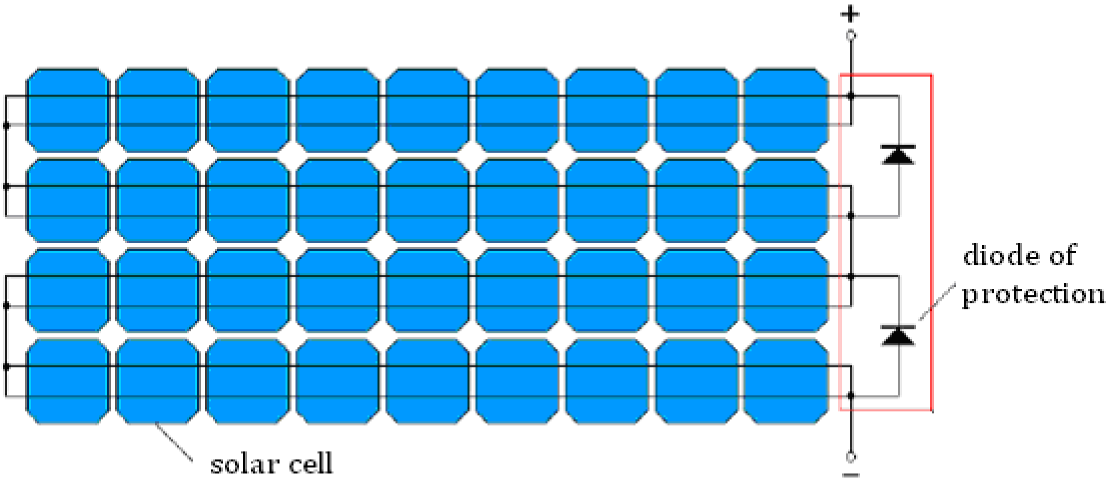

Fig. 1.4 Connetions of solar cells and bypass diodes

From that so far shown we can deduced that under the standard conditions of test, the electric behavior of the photovoltaic module is, scaled, very similar to that of a solar cell: particularly, the panel preserves the characteristics of a DC power source and keeps showing only one point of maximum power dependent on the irradiance and the temperature. Nevertheless, because of the interconnection series-parallel of the cells that constitute the solar panel, it can have a different electric behavior from the attended one if it doesn't operate under conditions of uniform irradiance since the set of cells with smaller irradiance will limit the current that should cross it, decreasing therefore the level of power supplied by the whole solar panel.

2.3.3 Photovoltaic Generator

With the same constructive principle of a solar panel, it is possible to build a photovoltaic generator simply interconnecting solar panels in series and/or parallel.

We can build PV generators of different power depending on the total number of used panels: connecting the panels in series or in parallel we combine separate levels of voltage and current. If the modules have identical electric characteristics and they operate in the same conditions of irradiance and temperature, we can affirm that the electric characteristics of the PV generator present only one point of maximum power whose value will be the sum of the maximum powers of each panel. Of course, said point will vary with the irradiance and the temperature of the operating location in which the PV generator will be built.

2.4 Power Processing System: Inverter

The inverter is the electronic device that deals with the conversion of the DC energy supplied by a PV generator into an AC electric energy in a way that it can be injected in the grid. Its finality consists of extracting the maximum available energy from the PV generator and to adequately inject it into the grid.

Every inverter used in PV system must fulfill the following tasks:

- Extract the maximum available energy from the PV generator. This implicates the use of subsystems that implements algorithms of pursuit of the point of maximum power (MPPT: Maximum Power Point Tracking) from the generator.
- Realize the conversion from DC to AC current involving the maximum possible energetic output with maximum efficiency.
- Realize the conversion DC – AC producing a very low electro-magnetic interference.
- Inject the current to the electric grid according to some determine norms of quality that implicate a limited harmonic distortion and with a high power factor (very close to the unity).
- Respect determined safety requisites for the consumers and the electric grid owing society.

In this thesis we don't enter into detailed explanations of the various mentioned points and we will consider the inverter working under ideal conditions, we will enter into details only about how to improve the efficiency of the energy conversion process for given operating conditions.

The choice of the inverter for a given PV generator follows a series of calculations that are function of the dimensions of the PV generator itself, of its maximum output power (which is a function of the geographical location in which the PV installation is realized), and it is dependent on the environmental conditions, from the same nature of the panels themselves and from possible system accessories (e.g. sun-tracking system).

In some studies it has been introduced a parameter called *Sizing Factor* (*SF*) and have been developed a procedure for individualizing the *Optimal Sizing Factor* (SF_{opt}) through which, knowing the power of the PV generator and considering various environmental conditions of influence, the value of nominal power of the inverter that maximizes the yearly energy injected in the grid (YIE) has been drawn [2][3].

A further study shows, through simulations and experiments, that using some opportune configurations, in which it is possible to unite or to separate PV generators and/or inverters, it is possible to increase of a certain amount the energetic efficiency of conversion between the output of the PV generator and the output of the converting power stage which is the energy injected into the grid [4].

The configuration that we will analyze through this thesis and we will verify is note as *TEAM System* [4].

2.4.1 Inverter Efficiency

The factor that more influence the efficiency of an inverter is the presence or not of a transformer for isolation. In some countries by law it is requested a isolation being between the electric grid and the PV generator. This isolation between grid and generator can be done using transformers of low frequency, 50 Hz or transformers of high frequency.

The inverters with transformer of low frequency can reach maximum efficiency around 92%, while those that use transformers of high frequency reach efficiencies up to 94%. If the transformer of isolation is eliminated, the maximum efficiency of the inverters can increase of two points more.

The output of an inverter is normally pointed out using the normalized measure note as "European-efficiency". It is valid for the levels of irradiance in some European countries and it is defined as a function of the efficiency of the inverter at determine percentages of its nominal power in AC as shown in equation (1.1), and if the PV generator is endowed with solar tracking system then the European-efficiency is redefined as shown in equation (1.2)

$$\eta_{EU} = 0{,}03 \cdot \eta_{5\%} + 0{,}06 \cdot \eta_{10\%} + 0{,}13 \cdot \eta_{20\%} + 0{,}1 \cdot \eta_{30\%} + 0{,}48 \cdot \eta_{50\%} + 0{,}2 \cdot \eta_{100\%} \tag{1.1}$$

$$\eta_{EU} = 0{,}5 \cdot \eta_{90\%} + 0{,}5 \cdot \eta_{100\%} \tag{1.2}$$

This is because the value of efficiency of an inverter is function of the power involved in the process of conversion of the energy.

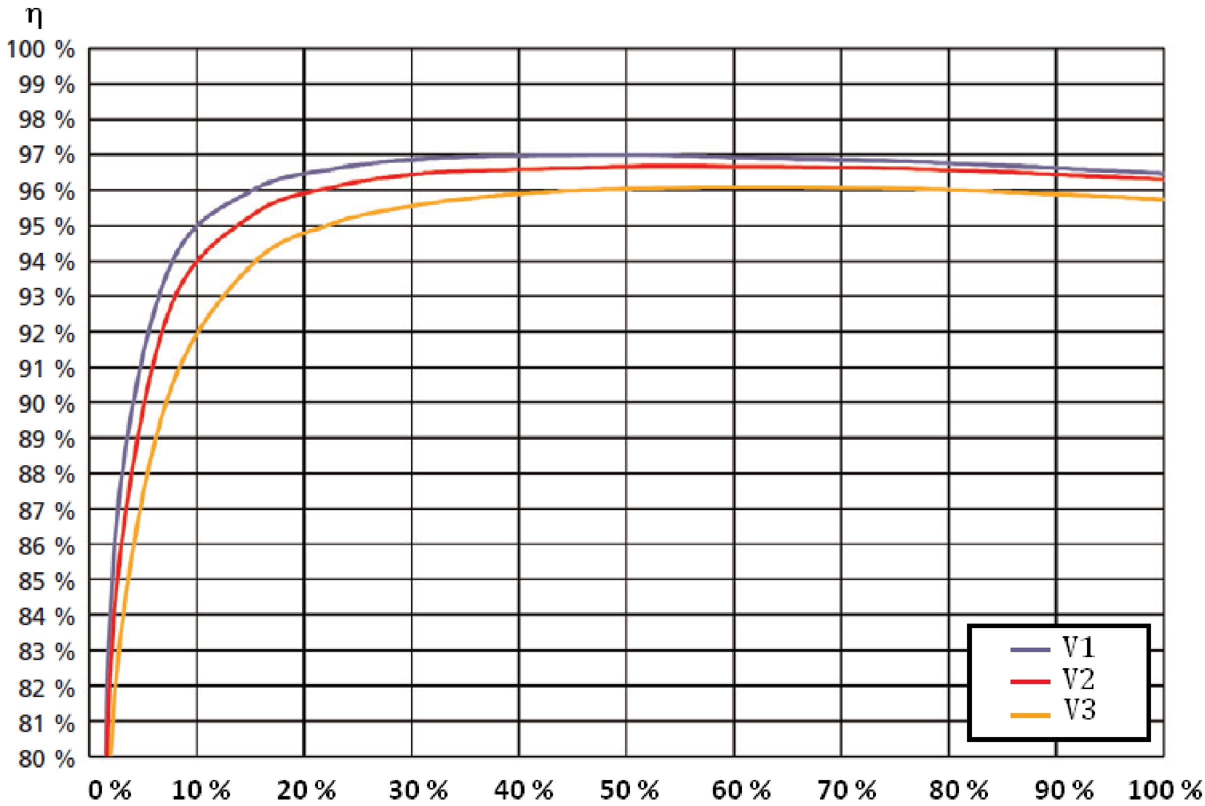

Fig. 1.5 characteristic of efficiency for inverters with variations of the load and for different values of the voltage. (V1<V2<V3)

The efficiency of an inverter is reported to the level of power that is supplied at its input. The figure 1.5 shows out that when the inverter operates under conditions of partial load conditions, lower than a 10% of its maximum power, its efficiency will be low.

The conditions of load of an inverter will depend on the maximum power of the inverter (note with P_{INV}) and of the power that is converting which is the power at the output of the PV generator which, in turn, depends on the environmental conditions where the generator is located and on its nominal power (P_{GF}).

Therefore, given a PV generator of one determined nominal power, the efficiency with which its output power will be converted will depend on the maximum power of the used inverter. Accordingly known the nominal power of a PV generator of a solar installation connected to grid, one of the most important decisions to be taken it will be the election of the maximum nominal power of the inverter to use (P_{INV}) with the goal to optimize the relationship between produced energy and cost.

It is intuitive to think that most of the time the generator will work in worse conditions than those standard (STC) and that, therefore, will supply a lower power than the nominal one to the inverter; this has brought the experts in past to think that a choice of an inverter with lower maximum power would have been a better choice in order to reach a higher conversion efficiency.

This can be true considering as time of test relatively short period of time but in terms of energy injected into the grid on annual base, the choice of an inverter with a low maximum power isn't always the best solution in terms of efficiency.

It has been then introduced a new parameter called *Sizing Factor* (*SF*) which is the ratio between the maximum power of the inverter and the nominal power of the PV generator (1.3):

$$SF = \frac{P_{INV}}{P_{GF}} \tag{1.3}$$

The practice of choosing the power of the inverter lower than that of the PV generator is known as *under-sizing* and corresponds to a SF<1 (even 20-30% lower than the unity).

The choice of the sizing factor for an installation is a theme of big interest and implicates a study in order to find the value that can maximize the energetic production of the installation.

Being the environmental conditions in which the PV generator is located varying over a huge range of values and over ample periods of time it is intuitive to suppose that the value of the optimal sizing factor is not a static value. Towards this directions moves the study of dynamic PV systems as later on explained.

2.5 Photovoltaic Generator Configuration

As we have said, the part of the PV generator is the one dealing with the conversion of the energy coming from the sun in electric energy while the inverter (or the inverters) connected to the output of the PV generators is the part of the system that extract from it its maximum power.

Given a certain number of panels the first task we face is deciding how many PV generator we want to make out of these panels. Grouping the panels we determinate a certain numbers of generators or sub-generators and in this way we determinate the part of the PV system which deals with the conversion of energy from solar to electric DC. Every sub-generator so made implicated a series of information from which starts the power dimensioning of the elements that constitute the second part of the PV system where the electric energy is converted from DC to AC, the inverters.

From the choices taken and with the information coming with those we can calculate the total efficiency of conversion of the PV system.

So far we made no choices, yet, because there is something more to say before being able to take decisions. We want to introduce now the possible configurations with which we can arrange a PV generator and according to this we see that there are different architectures focused on the panel, on the inverter or a type mixed.

These options are based on the type of connection in series and/or parallel of the available panels to the input of the inverter as following:

- Architecture aiming at the inverter: Plant Oriented (PO) configuration or single central inverter.
  This configuration is base on the interconnection series-parallel of the totality of the available panels, forming so a whole single PV generator connected to a single central inverter. It is an architecture of low cost and therefore very commercially used but introduces disadvantages in terms of modularity for the difficulty to expand the installed power but also in terms of efficiency because when the panels don't operate under the same conditions of irradiance and/or temperature or there are dispersion in their electric characteristics the resulting effects are losses in efficiency.
- Architecture aimed on the panel: Module Integrated (MI) configuration.
  In this configuration any PV panel is directly connected to its own inverter and the output of the inverters are connected directly to the grid. The tracking of the point of maximum power of every panel allows to extract the maximum possible energy from all the panels, being this the configuration that introduces the most greater level of modularity and, therefore, a high reliability and a big flexibility in terms of extension of the number of panels. The disadvantages introduced are represented by the difficulty of design inverters with a boost of their output voltage according to the restrictions of the grid and, obviously, the high cost of having so many inverters as the number of panels is. These problems make it not a very commercial solution for a plant.

- Mixed Architecture: Module Oriented (MO) configuration.
  Between the previous configurations we place this one which is a compromise among the complexity in terms of design, cost and output of the inverters and the total quantity of energy that it is possible to extract. The architecture is quite simple, sets of panels are connected in series and every set is connected to one independent inverter then connected to the grid. The series grouping increase the output value of voltage that must be processed by the inverter and this makes the design of the inverter simpler. Besides, it is certainly a more economic solution of that MI and introduces some advantages in terms of efficiency in comparison to that PO.

The three introduced configurations have in common that is impossible to modify in real time the interconnections among panels inside the PV generator and/or the interconnections among PV generators and inverters. For this reason they are defined as *static configurations*, and the PV systems using them can be grouped under the generic denomination of *static configuration PV systems*.

A clear relationship exists among the available power to the exit of the PV generator and the environmental conditions to which the panels are located. Giving a certain degree of flexibility to the interconnection of the panels, or the inverters, or to both, introduces an option that will allow the system to suit itself dynamically to the operating conditions of the solar panels, increasing, accordingly, the energetic production of the whole installation.

The PV systems endowed with flexibility in the interconnection among the lists parts that form them, adapting themselves to the environmental conditions, are noted as *dynamical configuration PV systems*.

The dynamical configuration PV systems can be distinguished according to the reconfigurable parts of the system itself. Anyway, the definition of the scaling factor SF defined as the relationship among the maximum power of the inverter and the nominal power of the PV generator connected, allows to realize a more general classification of the grid connected PV systems, a classification function of the type of reconfiguration.
A first classification can be made considering the evolution of the SF value, therefore, we can distinguish among systems that dynamically operate with constant scaling factor or with adjustable scale factor:

- Systems with constant scale factor:
    - Static conception: neither the PV generator neither the system processing the energy is reconfigurable.
    - Conception ‘EAR’ (Electric Array Reconfiguration): Only the interconnections among the panels of the PV generator are reconfigurable so that the nominal power of the generator and the maximum power of the inverter (which is one - static configuration with one central inverter) are constant.
- Systems with adjustable scale factor:
    - Conception ‘MIX’ (Master Inverter Exchange).
      In this configuration the nominal power of the generator doesn't vary while the power of the inverter is automatically adapted modifying its value of maximum, this means that it is the power processing part of the system the one reconfigurable.
    - Conception ‘TEAM’.
      In this configuration the maximum power of the inverter is fixed but the nominal power of the PV generator varies dynamically and so it is the part of generation the one reconfigurable.

The purpose of the systems with dynamic scaling factor is that to adjust the scaling factor to value the nearest possible to the optimal scaling factor during the whole cycle of evolution of the PV system accordingly to the evolutions of the environmental conditions.

2.6 TEAM Systems

The term TEAM is an idea of SMA and points out the concept of team work of the inverter introduced in the series Sunny Boy and Sunny Central of the products SMA.

The objective is to modify the curve of output of the inverters to improve the efficiency of conversion of the energy in the region of the characteristic in which the PV generator is supplying energy to the inverter and where usually the efficiency of one inverter is very low. We have said, in fact, that when an inverter works under the 10% of its characteristic, the efficiency of conversion is very low.
Adapting the curve of efficiency in function of the load or, as better said, in function of the energy supplied by the PV generator, we can increase the efficiency in condition of partial load increasing, therefore, the annual energetic production of the whole PV system and the total average efficiency.

When these systems operate under conditions of high irradiance, we can imagine the PV generator an array of *basic generators* each one made of a string of solar panels connected in a certain way, we might think about the mixed structure MO, for example. Every single basic generator is connecter to an inverter.
When the irradiance decreases, the system, reconfigurable, associate in parallel these basic generators in order to form a new system MO where every generator is connected to a minor number of inverters. This will modify the SF of the system and it implies that some inverters will be disconnected from the PV generator.
Further decreasing the irradiance, the system can reconfigure again and again till all the basics generators will be arranged to form only one PV generator which will be connected to only one inverter. We understand that the numbers of possible associations of these basic generators is the same number of possible different SF we can realize and we also understand that to the maximum number of basic generators corresponds with the number of the inverters needed.

The adjustable process is valid both ways, for irradiance increasing as well as decreasing.

So, the number of basic generators, the number of inverters and the number of possible different values of SF is the same. In an ideal continuous system, with endless number of basic generators and endless number of inverters, we could adjust the SF value to be exactly equal to the optimal SF value for all the points of the characteristic of transformation of the energy.

Obviously this is not a physically realizable solution and therefore it is not possible to obtain a value of SF equal to that optimal but, fixed a certain number of ranges of energy, we can have an adjustable SF value in a discrete way for every range of energy determinate and, consequently, improve the efficiency characteristic in a discrete way as well.

The objective of this thesis is to esteem the energetic efficiency of the grid connected PV systems using a dynamic configuration (TEAM), and to compare the results achieved this way with those that we would get from a static system. This work will be done first through a simulation and then through a real experiment with real components.

To plan a dynamic TEAM system implies sizing the number and the power of the PV generators used and the number and the power of the inverters; by software, instead, we must determinate an algorithm of reconfiguration with the purpose to maximize the energetic efficiency of the whole system.

3 STATIC AND DYNAMIC PHOTOVOLTAIC SYSTEMS

3.1 Introduction

Before passing to the study of the dynamic systems, we want to solve and to calculate the parameters of interest for a static PV system.

The PV systems in static configuration are based on architectures with fixed interconnections where a dynamic reconfiguration of neither the PV generator neither the stage of power conversion is available.

The PV panel is the unity of base for the construction of a PV generator. We initially have to study the different aspects that influence the output power of the generator. Once known the parameters of influence on the power output of the PV generator it will be possible to determinate possible action that allow us to dynamically maximize such value of power through the use of reconfigurable PV systems as we will see later on.

The available output power of a PV generator built associating in a certain way a determined number of solar panels with the same nominal electric characteristics depends on three fundamental characteristics:

1. Climatologic characteristics of the location where the system has been build needed to evaluate the effects of the incident irradiance over the panels and the operative temperature of the panels themselves.
2. Constructive characteristics of the PV generator in terms of connections: there are positive and negative aspects for both series and parallel connections.
3. Electric characteristics of the panels themselves. The experts esteem around a 2÷3% the value of the losses in the energetic production of the PV generator respect to the esteemed production, due to the dispersion of the electric characteristics (aging of the panels, mismatching, etc.)

We will determine the conditions in which it is possible to maximize the energy extracted by the PV generator with a static configuration supposing it under ideal operative conditions using solar panels with identical electric characteristics and operating to the same conditions of irradiance and temperature. We won't deal, therefore, with all the not ideal parameters internal (e.g. mismatching of the cells) or external (e.g. shades) to the solar panel.

3.2 Static Systems

3.2.1 Voltage-Current and Voltage-Power Characteristics

The curve characteristic current-voltage (c-vi) of a solar panel basically depends from the incidental irradiance on the solar panel and from the operating temperature. Quantities, these, that are certainly functions of the geographical position in which the plant is located, besides, obviously, the instant of time of the day and of the month in which we are measuring these quantities (supposing same meteorological conditions not varying from year to year).

The dependence of the curve c-v of a generic solar panel with the irradiance and with the temperature is shown in figure 2.1.

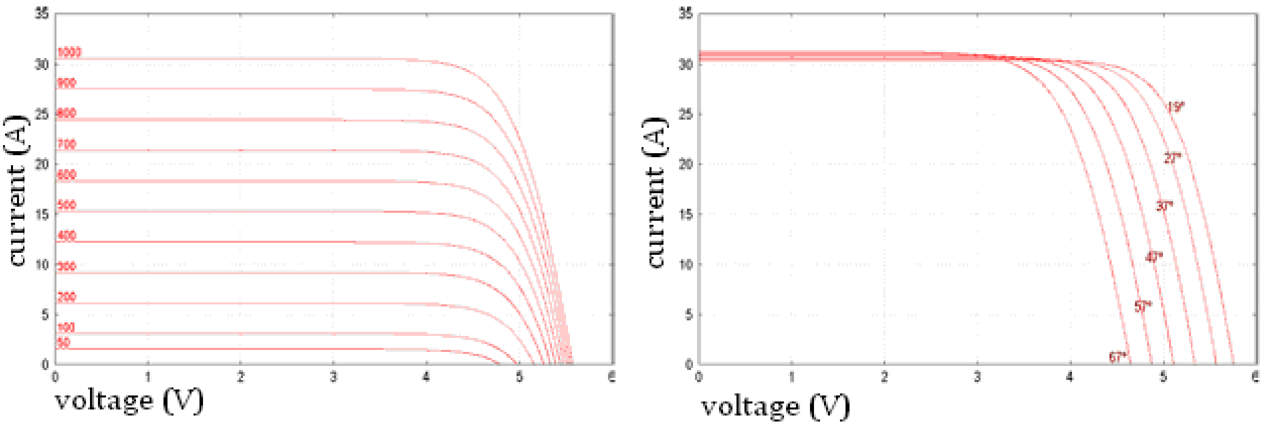

Fig. 2.1 characteristics current-voltage of a solar panel:
a) under different levels of irradiance (between 1000-50 W/m^2) and constant temperature of 27°C;
b)under different levels of temperature (19-67°C) and a costant irradiance of 1000 W/m^2.

While the dependence of the characteristic power-voltage (v-p) of a solar panel with the irradiance and the temperature is shown in figure 2.2.

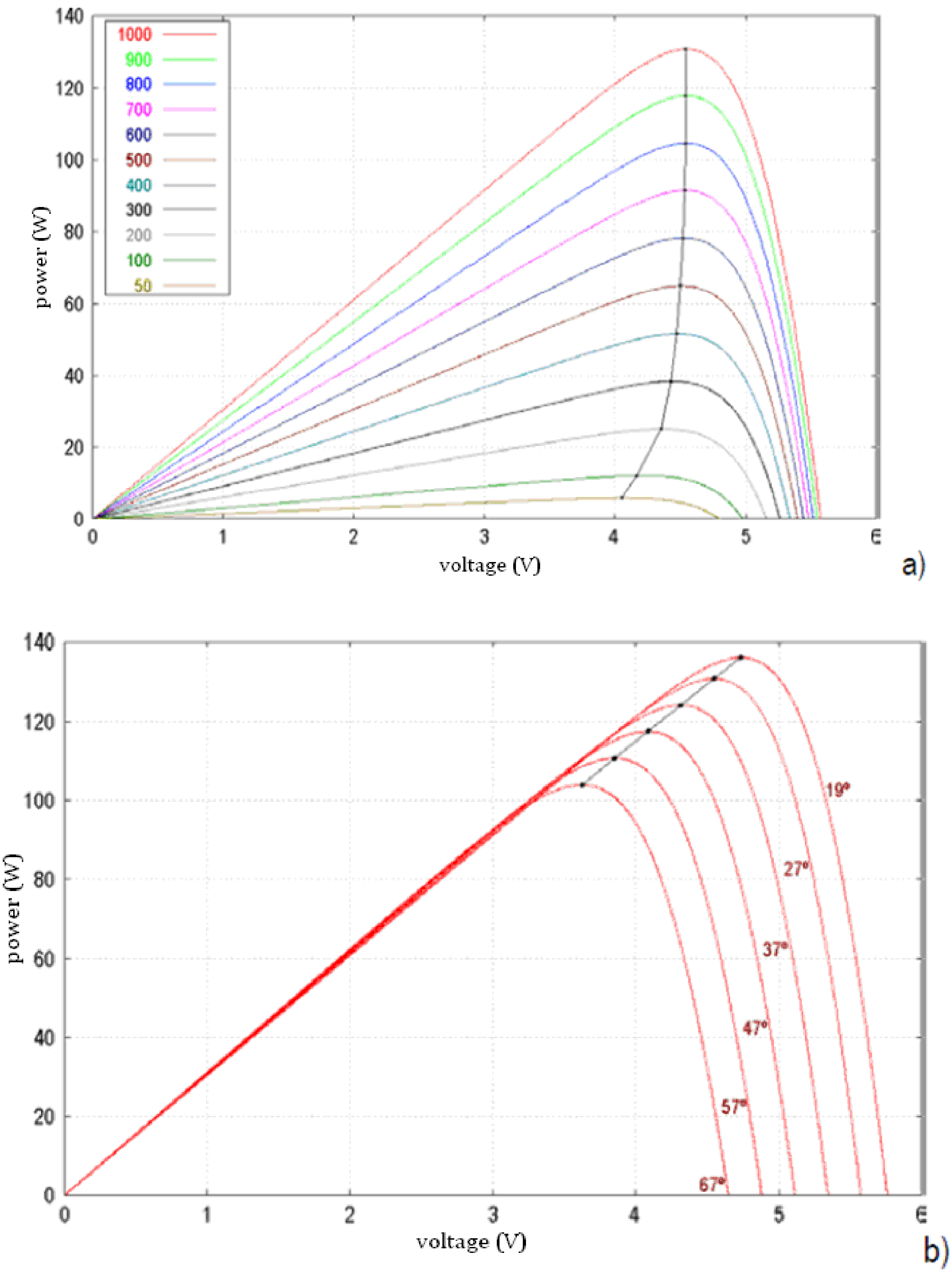

Fig. 2.2 characteristic power-voltage of a solar panel:
a) under different levels of irradiance (between 1000 and 50 W/m^2) and costant temperature of 27°C;
b) under different values of tempertature (between 19 and 67°C) and costant irradiance of 1000W/m^2.

We notice that the voltage of the maximum power point of a solar panel is practically constant for values of irradiance superior to 200 W/m^2 while the current directly changes proportionally with the irradiance.

"The available power at the PV generator output (P_{DC}) depends, among others, on the solar irradiance and temperature of the PV system location. The irradiance level and ambient temperature values are dependent on the PV site location latitude, longitude and altitude. Therefore, it is assumed that the SF optimal value will exhibit this kind of dependence" [3].

3.2.2 Photovoltaic Generator Model

The available power at the PV generator output (P_{DC}) depends on the incident irradiance (G), the PV modules operating temperature (T_M) and its efficiency (η_1) and can be modeled as:

$$P_{DC} = \eta_1 \cdot G \cdot [1 - \beta(T_M - T_R)] \cdot S_{GF} \tag{2.1}$$

Where:
η_1: PV generator efficiency at 25°C.
G: Incident irradiance on the PV generator's plane.
β: Thermal power coefficient of the PV generator material.
T_M: PV generator operating temperature.
T_R: Reference temperature (25º C).
S_{GF}: PV generator surface.
A constant value for both PV generator efficiency and thermal power coefficient of the PV generator material has been assumed, and fixed to the typical values of silicon mono-crystalline PV modules, namely $\eta_1 = 0.12$ and $\beta = 0.5$ %/°C. On the other hand, this work considers a static PV generator (i.e. with no sun tracking capability) oriented to the South, with a surface of 10 m_2. Taking into account the previous assumptions, the nominal power of this PV generator will be of 1.2 kWp.

Finally, the PV generator operating temperature (T_M) simulation model is defined as:

$$T_M = T_A + \alpha \cdot G \tag{2.2}$$

Where:
T_A: Ambient temperature.
G: Incident irradiance on the PV generator's plane.
α: Thermal coefficient of the PV generator according to mounting type.

The thermal coefficient value (α) exhibits a strong dependency with the PV generator ventilation capability (natural ventilation by convection, or forced ventilation by wind or airflows).

According to this work, the typical values of the thermal coefficient are fixed to α = 0.025 for PV systems on flat surface (flat roof) with good ventilation, and α = 0.050 for PV systems integrated in buildings where the PV generator ventilation is worse.

It is possible to demonstrate that the effects of variation of irradiance on the output of the PV generator are more consistent of those due to variations of temperature.

According to the equations (2.1) and (2.2) the maximum output power of a solar panel (P) is proportional to the incidental irradiance on the panels (G), supposing the operating temperature constant.

For example, for the temperature in STC, 25°C, P=0.132·G.

Contrarily, an increase of the temperature, T, to constant irradiance produces a decrement of the maximum power of the form (P).

For example, for an irradiance in STC, 1000 W/m^2, P = 149 – 0.667·T.

The temperature has, therefore, a very smaller influence than the irradiance on the maximum available output power of a solar panel.

3.2.3 Inverter Model

The available power at the inverter output (P_{AC}) will depend on both the input power (P_{DC}) and the inverter's efficiency (η_2):

$$P_{AC} = \eta_2 \cdot P_{DC} \tag{2.3}$$

There are some mathematical models in the literature to represent the inverter's efficiency curve in terms of the input power P_{DC} or output power P_{AC}.

With the purpose of generalizing these models to any type of inverters, freeing them from the value of the maximum power of the inverter, it is possible to make a characterization of the inverter efficiency η_2 using the value of the normalized input power (p_{dc}). This value of power is determined as the ratio of the input power to the inverter (P_{DC}) and its maximum power (P_{INV}):

$$p_{dc} = \frac{P_{DC}}{P_{INV}} \tag{2.4}$$

This work has considered a model which is applicable for input power ranges P_{DC} lower than the maximum inverter power, designed as P_{INV} or, in other words, for p_{dc}<1.
The efficiency of the inverter (normalized on P_{INV}) is given by the following equation (2.5):

For $P_{AC} \leq P_{INV}$
$$\eta_2(P_{AC}) = \frac{p_{ac}}{p_{ac} + k_0 + k_1 \cdot p_{ac} + k_2 \cdot p_{ac}^2} \tag{2.5}$$

Where:

$p_{ac} = P_{AC}/P_{INV}$
k_0 = losses coefficient at no load whereas
k_1, k_2 = coefficients corresponding to losses varying in a linear and quadratic way along with the inverter current.

The variation introduced in the model substitutes the normalized output power (p_{ac}) for the normalized input power (p_{dc}):

For $P_{DC} \leq P_{INV}$

$$\eta_2(P_{DC}) = \frac{p_{dc}}{p_{dc} + k_0 + k_1 \cdot p_{dc} + k_2 \cdot p_{dc}^2} \quad (2.6)$$

The simplification in the calculation process consists in starting from the power generated from the photovoltaic generator (P_{DC}), we calculate the efficiency $\eta_2(P_{DC})$ of the inverter through the (2.6) and the output power applying $P_{AC} = \eta_2(P_{DC}) \cdot P_{DC}$.
Now, with these results, we need to solve equation (2.5):

For $P_{AC} \leq P_{INV}$

$$\eta_2 = \frac{\left(\eta_2(P_{DC}) \cdot {P_{DC}}/{P_{INV}}\right)}{\left(\eta_2(P_{DC}) \cdot {P_{DC}}/{P_{INV}}\right) + k_0 + k_1 \cdot \left(\eta_2(P_{DC}) \cdot {P_{DC}}/{P_{INV}}\right) + k_2 \cdot \left(\eta_2(P_{DC}) \cdot {P_{DC}}/{P_{INV}}\right)^2} \quad (2.7)$$

For input power ranges greater than the inverter maximum power, this work assumes the following inverter mode of operation: the inverter's control will limit the input power to its maximum value until the overload conditions are no longer present, ensuring the output power delivery with no interruptions.

Under these assumptions, the inverter's efficiency can be properly modeled by the following hyperbolic dependence:

For $P_{DC} \geq P_{INV}$

$$\eta_2 = \frac{\eta_{2(p=1)}}{p} \quad (2.8)$$

Figure 2.3 shows the inverter's efficiency curve for the set of parameters k_0=0.0274, k_1=0.822, k_2=0.1233, which closely match the efficiency curve of a commercial grid-connected inverter with low frequency isolation transformer.

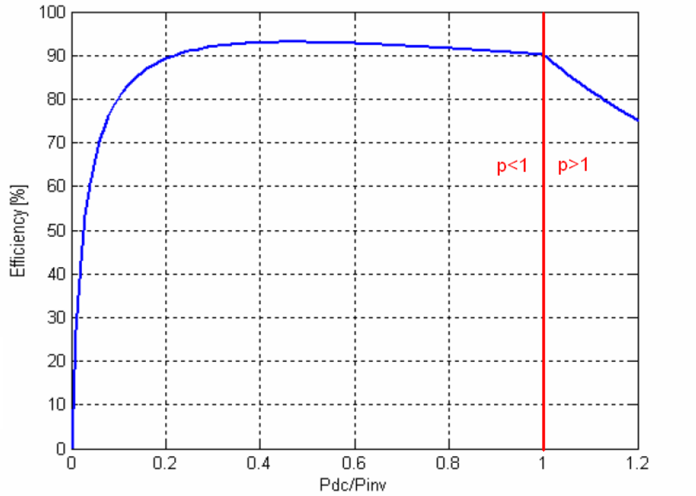

fig.2.3 Inverter's efficiency curve considering the overload losses

Evidently, there are other many aspects that can affect the inverter's efficiency such as thermal protections or the inverter's input voltage range. These aspects are out of the scope of this work and, therefore, will be not considered.

3.2.4 Energetic Efficiency

In order to evaluate the efficiency of a PV system, whereas it is static or dynamic, it is necessary to use a parameter of comparison. For this reason we introduce a parameter called *energetic efficiency* and it is so defined:

$$\eta_E(SF) = \frac{E_{AC}}{E_{DC}} = \frac{\int_0^T P_{AC}(t)dt}{\int_0^T P_{DC}(t)dt} \tag{2.9}$$

Where T is the particular time interval we are considering but, generally, to compare PV systems, T is fixed as one year and then the parameter of comparison is the yearly injected energetic efficiency of a PV system.

We want to underline that this parameter is a function of the sizing factor (1.3) previously introduced and, in fact, the search of the so called optimum SF is the value that maximizes the energetic efficiency of the installation so that we can define:

$$\eta_E(SF_{opt}) = max\left(\frac{E_{AC}}{E_{DC}}\right) = max\left(\frac{\int_0^T P_{AC}(t)dt}{\int_0^T P_{DC}(t)dt}\right) \tag{2.10}$$

From the previous expression an important observation is that SF_{OPT} depends on the period T in which the energy efficiency is evaluated, this means that there are different SF_{OPT} values depending on what T has been chosen or, said in other words, the SF_{OPT} is not a static value.

The figure 2.4 [1] sample the block-diagram used to calculate the optimum sizing factor using the models described previously.

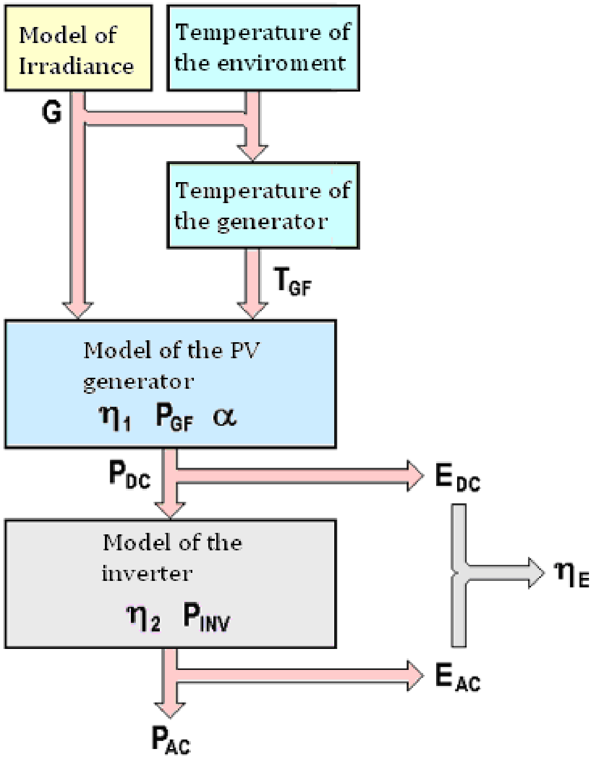

Fig. 2.4 Block-diagram for calculating the optimal sizing factor.

Starting from the monthly curves of irradiance (G) and ambient temperature (T_A) the operating temperature of work of the photovoltaic generator is determined (T_{GF}). Given operating temperature, the irradiance and the model of the generator, we obtain the available output power of the generator (P_{DC}) and the value of the available annual energy in the photovoltaic generator: E_{DC}.

Starting from the available power of the generator and using the efficiency model of the one inverter, we can determine the power to its output (P_{AC}) and the annual energy injected to the electric grid: E_{AC}. With the data of available energy of the generator and energy injected into the grid we can esteem the energy efficiency of the installation η_E(SF) as previously defined.

We want to point out the following info:

The interval of time used to get data on the irradiance and, consequently, on P_{DC} must be about the order of 10-15s since with larger interval of time we lose the important power contribute included into fast transients of irradiance and this implies less detailed measurements and considerations. Commonly, hourly averages are used but “using a low time resolution radiation data tend to overestimate efficiency and underestimate losses”.[5]
The available power at the PV generator output (P_{DC}) is almost directly proportional to the solar irradiance picked up by the PV generator and depends from the site geographical lo-

cation and the time of the year considered. Consequently the optimum sizing factor will also vary with the location and the time of the year considered.

As earlier said, the optimum SF depends on the T period in which the energy efficiency is evaluated. The election of an annual period for the evaluation of the SF_{OPT} it is aimed to the design of photovoltaic facilities of static configuration, since on one hand it is assumed a certain grade of annual rhythm inherently in the evolution of the meteorological variables. On the other hand, the period of one year is the habitual one when evaluating the energy production of an installation [1].

On the contrary, if a period of calculation of one month is used, or of one day, we will obtain the monthly or daily evolutions of the SF, variations that will allow us to design photovoltaic systems with dynamic configuration where the value of SF is variable and adjustable to evolving operative conditions of the system. This way, the energy efficiency of the photovoltaic installation will be analyzed for different values of the SF, being possible then to determine which one will maximize the energy production (conversion) of the system.

3.3 Dynamic PV Systems

3.3.1 Energy Efficiency Improvement With Adjustable Sizing Factor

"The energy efficiency improvement of reconfigurable grid-connected PV systems where either the installed power of a PV generator assigned to a power processing stage constitutes a degree of freedom of the PV system operation. The work [4] suggests a reconfiguration strategy driven by the estimation of the Sizing Factor (SF) which optimizes the Yearly Injected Energy (YIE) "… and the reconfigurable PV system can be considered as a PV system with a dynamic adjustable SF which tries to fit at any time the SF optimum value maximizing the YIE." [4]

Once designed a PV generator it is necessary to design the power stage which means to select a certain number of inverters, at least one, in order to inject, properly, the energy extracted from the PV generator into the electric grid.

A criteria that we can call "choice of the optimum Sizing Factor" has been given so that after a certain considerations and calculations, there is a guide to choose the maximum power of the inverter or inverters. This is the cookbook for static (not reconfigurable) PV systems.

Moreover, once chosen a location where to build the installation, we have said that the SF isn't a fixed value but varies with time and time interval. For example with a time interval of one month ideally we have 12 different SF along a year.

The aim of reconfigurable PV systems is to create conditions in which the SF of the whole PV system have a certain degree of freedom to adjust with time in order to adapt itself as closest possible to the value of SF_{OPT}, instant by instant or, in other words, to make the system injecting the maximum energy amount possible, instant by instant.

As introduced in the first chapter there have been developed 2 ways to create a reconfigurable PV system which are MIX concept and TEAM concept.

Within this thesis we want to pay our investigation on the TEAM concept.

3.3.2 TEAM SYSTEM

The reconfigurable photovoltaic systems based on TEAM concept can modify the SF modifying the value of the nominal power of the photovoltaic generator connected to a power stage processor with constant maximum nominal power.
Said with different words we can imagine a PV generator made of a certain number of sub-generators and when they are all connected they give the maximum nominal power of the PV generator. It has been demonstrated [1] that the best efficiency of the system is reached when all the sub-generators have the same nominal power which means that they are build with panels of the same type in the same number and configuration.
The resulting PV generator is connected to a power stage of conversion made of *m* inverters, with the same maximum power, where *m* is the number of sub-generators.

According to the amount of available irradiance incident into the solar panels, the team system works in the following way and it has been shown in figure 2.5:

- When the irradiance is low, the generators are all connected together to form one generator which is connected to a single inverter while the other inverters are disconnected. This way we are working with a certain SF_1. We recall the fact that the inverter efficiency is low when its load is low so, this way, we are maximizing the load at the input of the inverter in order to improve his efficiency under low load circumstances or, equivalently, we are adapting the SF to a discrete value that maximize the efficiency of the system in low load input conditions.
- When the irradiance reach a certain pre-determinate value, the system re-arrange the configuration of the PV generator, let say that it splits in 2 sub-generators connected to 2 different inverters of same nominal power. We are then using a new value SF_2 which improves the efficiency of the system under new different circumstances in terms of solar energy irradiating the panel.
- Considering the case of 4 sub-generators, it means that the system is capable of dividing the original PV generator in 4 sub-generators to which corresponds to another different value of the sizing factor SF_3.

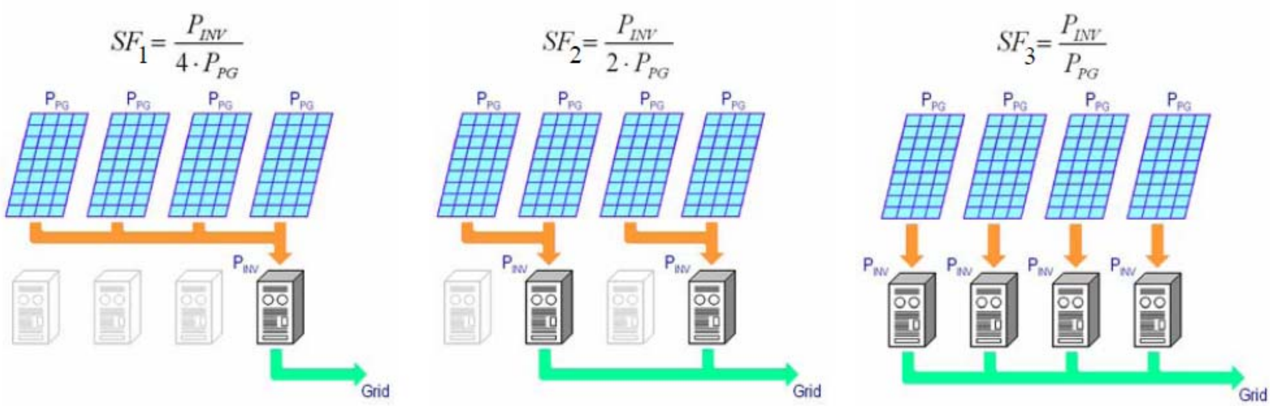

Fig. 2.5 The three possible configurations and the corresponding SF for a team-based system with 4 available sub-generators

Without losing in details we can say that the evolution of the PV system based on team concept allows a reconfiguration of the PV generator according to the variations of irradiance, be it increasing or decreasing, and that there are *m* possible sizing factor values if it is possible to divide the PV generator in *m* possible sub-generators with *m* available inverters.

We expect that when the sub-generators are all connected separately to their inverters, the power AC of the reconfigurable system is the same of a static system but we also expect an improvement of efficiency when the system reconfigures to adapt the sizing factor to optimum values in conditions of low load with a consequently improvement of the yearly injected energy amount.

The finality of this thesis is to verify the mentioned hypothesis about the TEAM system concept and to measure experimentally the amount of improving efficiency of such system compared with a static system under the same operative conditions.

4 EXPERIMENTAL VERIFICATION OF THE DIFFERENCES BETWEEN PV STATIC SYSTEMS AND TEAM-BASED PV SYSTEM

4.1 Introduction

With this thesis we want to verify the hypothesis at the basis of the TEAM system concept, demonstrating differences and, possibly, improvements using such design compared with the static systems.

We have mentioned previously some guidelines on how to choose the components needed to create a grid connected solar installation with a static or dynamic concept; now, we will apply some working conditions and we will quantify the difference in terms of energy injected in the grid for one same system applying the static concept first and the dynamic concept later.

Using a physically realized PV installation the curve of power representative of two typical days in Barcelona has been sampled. These databases are known as sunny and cloudy curves.

Working with a database, instead of a real PV generator, allows us to simplify the PV system model used, in fact, these data already include all the parameters of influence that characterize a PV installation and, for this reason, we can consider the evolution of the power along the day as the result of just one chosen parameter, i.e., the irradiance.

Moreover, the database, being univocally determined, implies the reliability of the experiments.

4.2 PV Installation in Laboratory

We want to compare the results in terms of power and energy that two PV systems, based on different concepts, present. To achieve these results we must be able to create working conditions which are defined and consistent in order to guarantee valid experiments that can be possibly reproduced and verified in future. It is necessary, therefore, specify carefully what these “working conditions” are.

A PV installation is made primarily of a PV generator made itself of solar panels. For this experiment we will not use a real PV generator but a simulator which is necessary in order to guarantee consistent working conditions as we will better explain later.

Injecting energy in the grid is possible using inverters and it must be a number of at least two units if we want to experiment the TEAM system concepts.

In order to connect different PV generators with different inverters it is necessary to use a system capable of checking the power extracted from each generator, determinate the instant of time in which a division or an association of such generators must be done and physically realize it. It is, therefore, necessary to build a board to place between the two mentioned sub-systems of the installation for making measurements and for controlling the relays needed for the reconfiguration of the PV system.

4.2.1 Solar Array Simulator

The Solar Array Simulator (SAS) is a device which simulates the behavior of a PV generator. These equipments can be programmed and produce the same output that we would find at the output of PV generator made of solar panels.

We needed to use simulators and not a real PV generators for the same reasons of consistency we introduced earlier: we said that we must guarantee the same working conditions for both the static system and the dynamic one, this would be not possible if we were using a generator made of solar panels because we cannot control the parameters of influence acting on it: the irradiance level for two following sunny days, for example, can be very similar but not identical. Using simulators we can get rid of the parameters of influence because we program the simulators in the same way for both the experiments and, let's say, we have a variation of the output power according to a variation of only one parameter of our choice, in this case, the irradiance.

The simulators we are using are Agilent SAS 4350b and Agilent SAS 4361A.

E4350B, E4351B

Fig.4.1 Solar Array Simulator Agilent 4350b and Agilent 4360A

In the configuration we are going to use they act as two PV sub-generators with the following limits:
P_{mp_max}=600W, V_{mp_max}=120V, I_{mp_max}=5A.
This means that the whole PV generator has a maximum output power of 1,2kW.

4.2.2 Database of curves

Using a real PV installation in Barcelona, data, about two typical days during the past year, have been taken and from them two databases have been created. The information representing the evolution of the power along the day, in terms of V_{mp}, I_{mp} and P_{mp}, for the specified days have been collected and stored into databases.

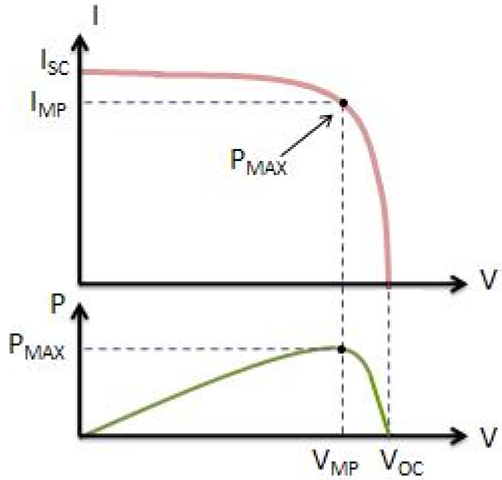

Fig.4.2 Graphical representation of Vmp Imp and Pmp

A first task has been being able to program the simulator starting from the data included into those databases. The Agilent SAS can be programmed as a PV generator only if the arrays are programmed feeding them with an array of the values representing V_{oc} I_{sc} V_{mp} and I_{mp} for every point of the characteristic of the power curve we want to simulate. This means that, starting from values of V_{mp} and I_{mp}, we needed to find values of V_{oc} and I_{sc} for every point of the characteristic. We didn't know how the original PV installation was made in terms of solar panels and configuration of them, it has been therefore necessary to assume a representative ideal model of the real PV generator. We have done it using an equation derived from the simplified model of Green [6 – Appendix B] where we assumed Np=1, Ns=72 and Rs=0.3Ω, T=300K and m=1.5.

$$I = I_{SC}\left[1 - \exp\left(\frac{V \cdot N_P - V_{OC} + I \cdot R_S \cdot N_S}{m \cdot V_T \cdot N_P \cdot N_S}\right)\right] \qquad \text{Eq. 4.1}$$

Once obtained all the data needed for every characteristic, we have made further data operations in order to adapt the absolute maximum voltage of the data to the maximum output of the simulator respecting the bonds of the power.

Finally, we obtain two representative curve files that we will be using to program the SAS.

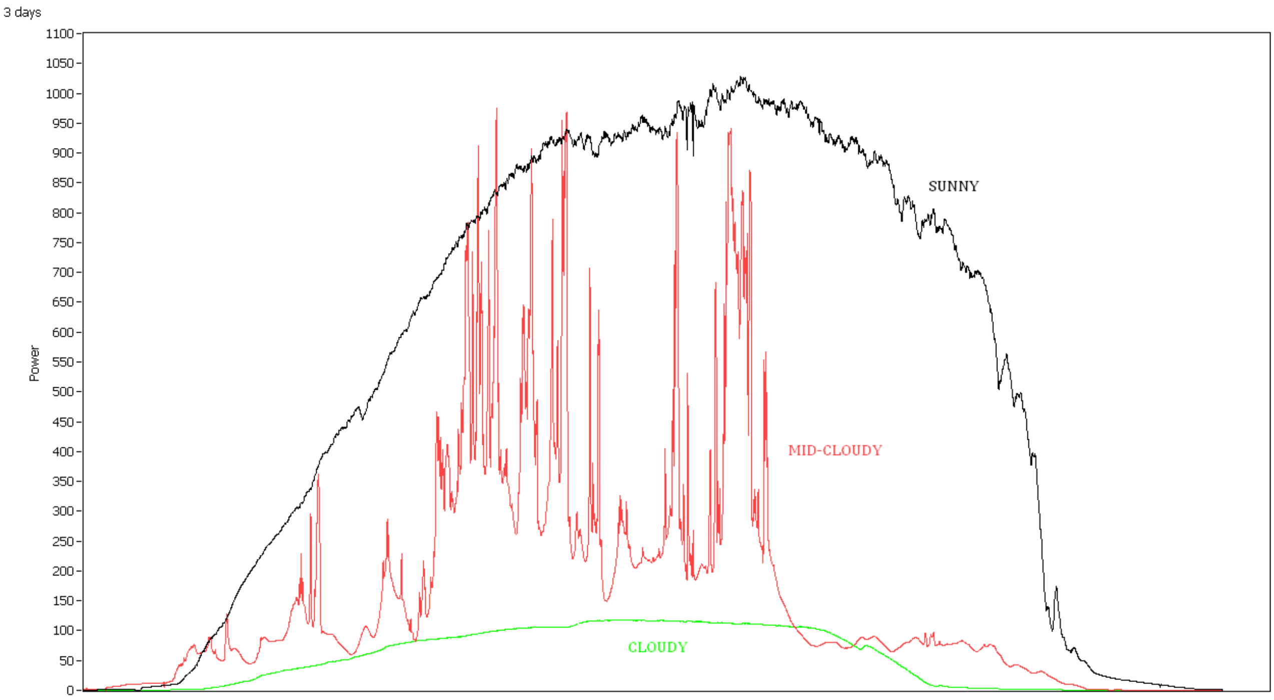

Fig 4.3 Graphical representation of sunny and cloudy curves.

4.2.3 Inverters

The inverters we are using for the experiments are Sunny Boy 700 made from SMA. Their input voltage range can be adjusted and, since the maximum voltage we can achieve with the SAS is 120V and since it is possible to choose the MPP (Maximum Power Point) input range, we chose the range [75 – 150]V with corresponding voltage start limit U_{PV_start} equal to 95V, nominal output power 460W and maximum input power is 550W.

Having the nominal power of generators and inverters set we can already calculate the sizing factor for the static and the dynamic configuration. Considering the nominal values:

1. Two generators associated with one inverter: $SF_a = \frac{Pinv}{Pgen_a} = \frac{460}{1200} = 0{,}383$;
2. Two generators associated each with one inverter: $SF_s = \frac{Pinv}{Pgen_s} = \frac{460}{600} = 0{,}766$.

The efficiency of the inverters, as earlier mentioned, is low when the energy supplied at their input is low, being able to reduce the sizing factor should result into an increase of the efficiency for low values of $\frac{P_{DC}}{P_{INV}}$, figure. 4.4.

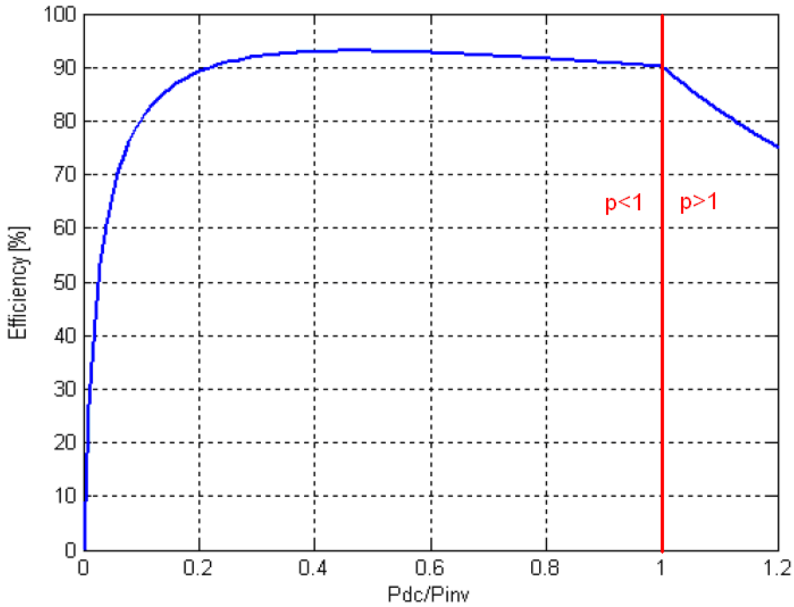

fig.4.4 Inverter's efficiency curve considering the overload losses

4.2.4 Control Board

The TEAM system, as already explained, allows a reconfiguration of the connection between generators and inverters. This can be done operating a control on a certain amount of relays according to the dimensions of the PV system and to the way we want to command the reconfiguration. It is therefore needed a board of connection between generators and inverters in which are present some relays and, on the same board, we also included the devices needed for the control. The control on the switching relays, in fact, is done through a continuous measurement of the power, current or voltage between generators and inverters and comparisons of these values with some threshold limits we derive from the used model.

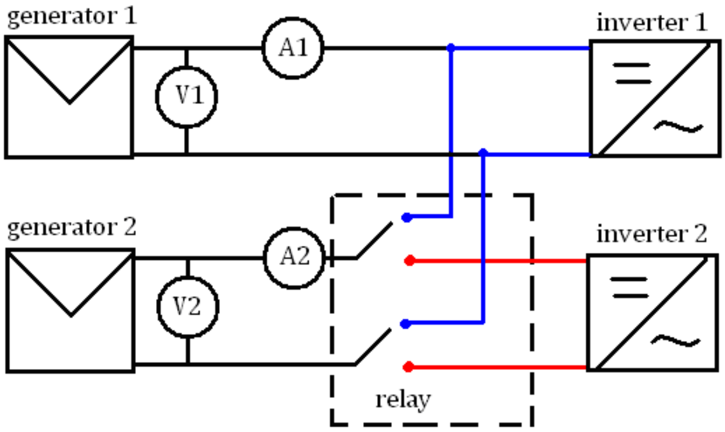

Fig. 4.5 Simple TEAM concept circuit schematic

4.2.4.1 Current Sensor

We used as current sensor the device LEM HY 10-P based on the Hall effect which senses current up to 10A and gives a voltage control signal from 0 to 4.8V.

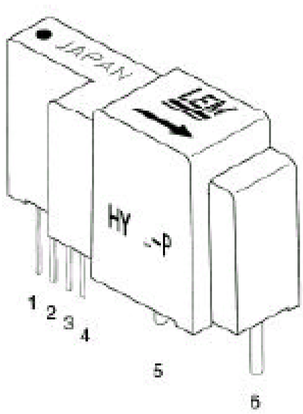

Fig. 4.6 LEM current sensor

4.2.4.2 Voltage Sensor

For the voltage sensor we decided to use a voltage divider considering that the maximum voltage at open circuit allowed from the SAS generators is utmost 130V. Using resistors of 33kΩ and 470kΩ the average factor of reduction about 1/15 which makes the output of the sensor being 8.53V when the voltage at the output of the generator is 130V. This choice is due to the limits of the acquisition board which are 10V for channel.

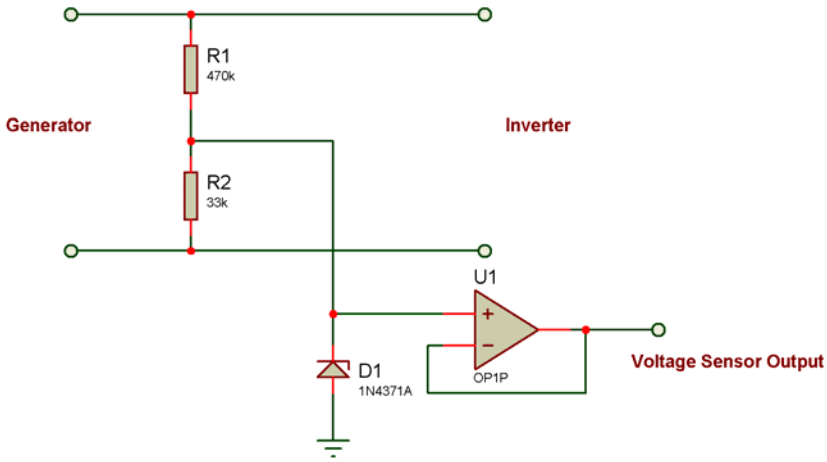

Fig. 4.7 Voltage Sensor

The voltage buffer has been used as an additional option to avoid loading effects at the input of the acquisition board even if the input impedance of the board is already quite big compared with the resistors of the voltage divider.
Besides, a Zener diode of 12V has been used to limit the value of the measurement in case of over-voltage that might possibly present at the input of the buffer and consequently at the input of the acquisition board causing damages.

4.2.5 Acquisition Board

We use the National Instrument NI 6249 acquisition board to acquire the values of voltage and current coming from the simulators that, as we said, act like PV sub-generators.

Fig. 4.8 NI 6259

Using a self-made or all-done sensor doesn't mean we can automatically use the values given from such devices the way they are, it is hard to have a pure factor of conversion according to the nominal values of the devices, a calibration curve for properly associate captured values with those effectively supplied from the simulators have been developed and used. Using polynomial algorithm of fitting, we derived a function that for every value supplied from the acquisition board allows us to recover the original value measured, be it current or voltage signal.

4.2.6 Relays

At least one relay is necessary to decide if the generators are supplying to one inverter or two.

The main relays used for the flow of energy from generators to inverters are Finder model num. 66.22.9.012.0000. They are DPDT relay with 12V coil control capable of switching 250V/8A or 400V/15A power sources.

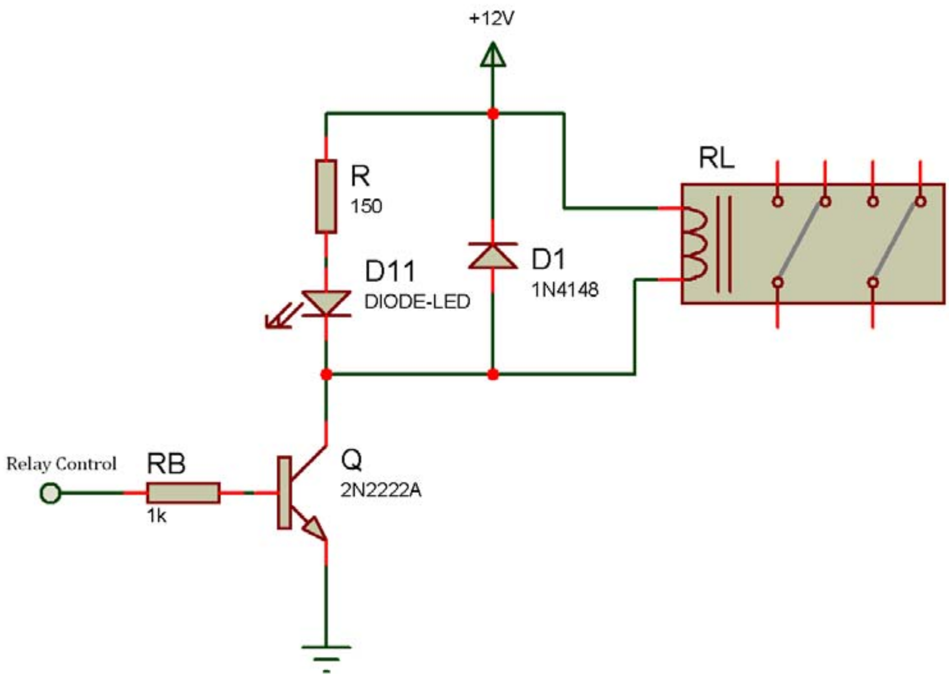

Fig. 4.9 Relay Control with led and circuit of protection

Since the NI 6259 acquisition board can be used also to control digital output of 5V, we designed and used a driver for the coil of each relay made of a transistor, resistors, protective diode and a led for a visual control of the state of the relay itself. The driver is necessary to inject power into the coil for commanding the switch and to keep its state during time since the relays used are NO (Normally Open) type.

When the static system is under tests, the sub-generators are straight connected to the respective inverters for all the time of the characteristic we are simulating. Instead, for the Team system, there are two power limits that specify the moment in which the two sub-generators stop supplying energy to one inverter and start supplying energy to both the inverters respectively, and vice versa. These two values of input power will be defined later on as Pd (power of division limit) and Pa (power of association limit).

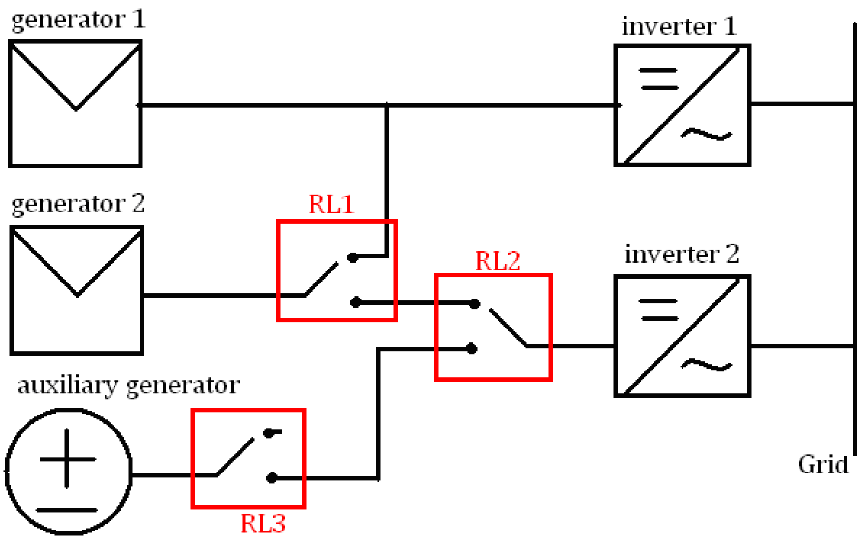

Fig. 4.10 Simple representation of the actions of the relays

About the relays:
RL1: allows the association or not of the sub-generators when they must supply energy to one inverter instead of two;
RL2: controls which supply is feeding the inverter two, if the sub-generator two or the auxiliary generator (which function will be later explained);
RL3: controls whereas the inverter two is being supplied from the auxiliary generator or not. Is not really necessary but has been installed to underline the function of the auxiliary generator and the led allows us to see when the auxiliary generator is actually feeding the inverter.

4.2.6.1 Power Limits for Relays Switching

If we define with P_{DC} the input power of an inverter, we can also define two limits of power P_A (association) and P_D (division) that fix the instant of reconfiguration of the TEAM system:

- $P_{DC} > P_D$ the generator must divide in two equal sub-generators connected to two inverters;
- $P_{DC} < P_A$ the sub-generators must associate in one generator connected to one inverter.

The value of power of these two limits is calculated applying criteria of maximization of the grid injected energy considering the efficiency of the inverters. We recall that from eq. 2.6

$$\eta_2(P_{DC}) = \frac{p_{dc}}{p_{dc} + k_0 + k_1 \cdot p_{dc} + k_2 \cdot p_{dc}^2}$$

Once fixed the input power of an inverter, its output power will be the maximum when it will work with the maximum possible efficiency, therefore, the process of reconfiguration must not imply a reduction of the efficiency for the active inverters while happening.
This implies that:

- An inverter must keep working with the same value of efficiency while dividing for two his input power:
  $\eta(P_D) = \eta\left(\frac{P_D}{2}\right)$
- An inverter must keep working with the same value of efficiency while multiplying for two his input power:
  $\eta(P_A) = \eta(P_A \cdot 2)$

Solving these math systems with the previous formula and according to the mentioned conditions we can evaluate $P_D \cong \frac{2}{3} P_{INV}$ and $P_A \cong \frac{1}{3} P_{INV}$ where P_{INV} corresponds to the nominal value of the inverter.

4.2.6.2 Auxiliary Generator

We are using the Sunny Boy 700 from SMA. While experimenting we have noticed that the average time the inverter needs in order to synchronize itself with the grid is around 80s.

Using an oscilloscope we have seen that for about 40s nothing really happens, seems like the inverter needs that time for internal operations. After this amount of time we noticed a peak of power every 1s for 40 times at the end of which the inverter is synchronized with the grid and the MPPT system start searching for the maximum power point.

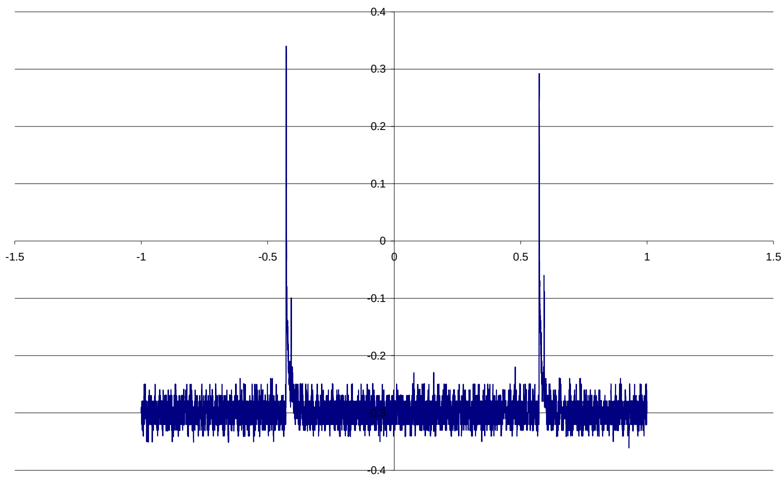

Fig. 4.11 Image taken with Tektronix oscilloscope, it shows two following points of synchronization of the inverter into the grid.

For the static systems the synchronization of the inverters starts at the beginning of the day and last all day long so there are no evident problems for that. For the TEAM system, instead, this synchronization need is a problem during the reconfigurations intervals.

Let's suppose that we don't want to take into account this problem, this means that when the system reconfigures and a sub-generator is connected to the inactive inverter, a time interval of 80s is wasted while the inverter synchronizes itself. The problem is even worse if we consider a particular variable day in which the power limits for reconfiguration are repeatedly crossed. A graphical example is the one shown in figure 4.12 in which the TEAM system without auxiliary generator has been considered for the sunny curve.

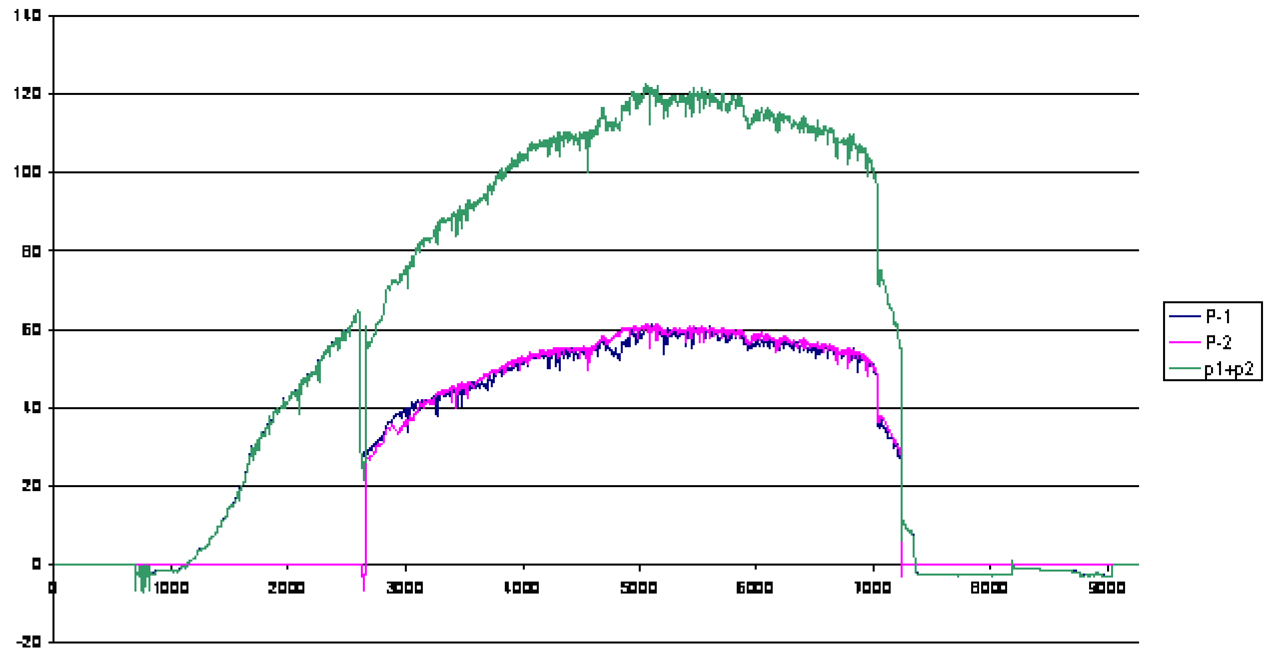

Fig. 4.12 TEAM system without auxiliary generator

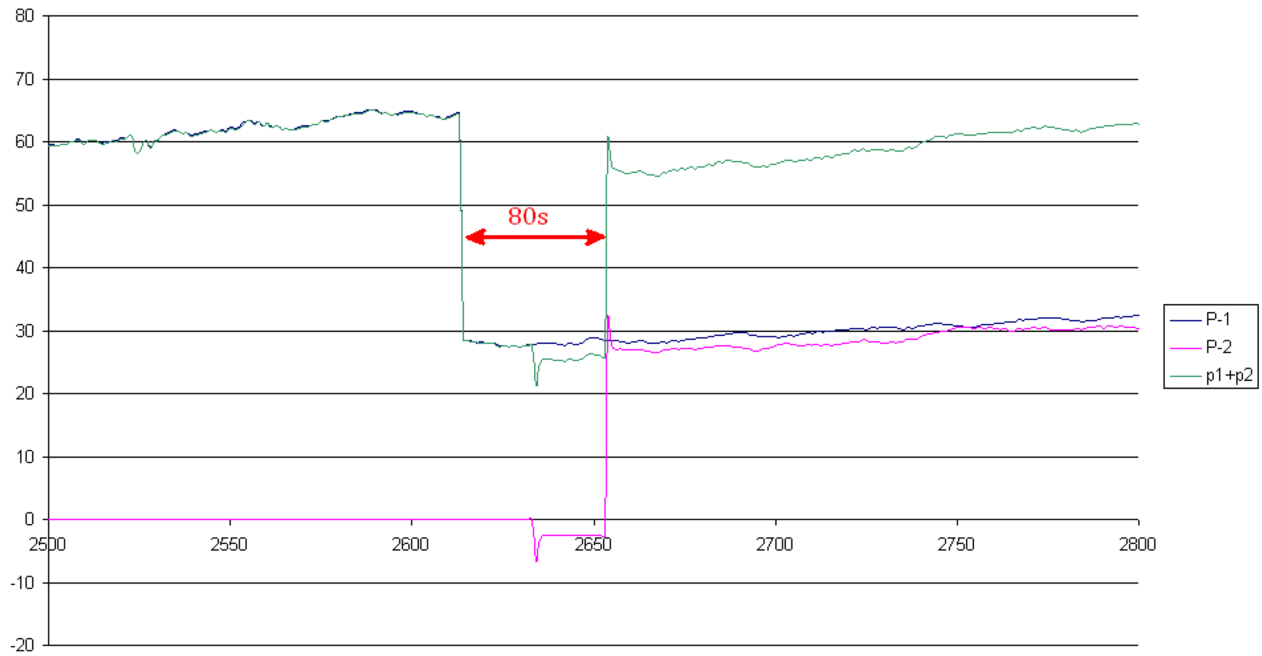

Fig. 4.13 TEAM system without auxiliary generator - Zoom

In figure 4.13 is even easier to see the effects of not using the auxiliary generator:

1. When the relay switches to allow generators to supply one inverter each we expect that the curve of power for the first inverter will be shorten of one half and, in fact, the blue characteristic steps down to a half of its previous power.

2. We expect that the curve of power for the second inverter steps up delivering half the power previously injected into the grid from the first inverter but this happens after about 80 seconds. In terms of energy we are being wasting eighty seconds of energy fed to the inverter but not passing through to the grid.

We want to point out some obvious consideration about the previous graphs:

a. The time scale is 2s/point, in fact, the number of points we count from the moment in which the sum of powers steps down to the moment in which it steps up is of 40 points which corresponds exactly to 80s. This is just a lucky case in which the correspondence is exactly 80 seconds but this number is to be considered as a nominal value and not an exact value.
b. Once the second inverter starts delivering energy to the grid the power characteristic isn't exactly the same of the first inverter; this is a quite normal consequence of the fact that the devices are not exactly the same even if from the same family and type, besides, the energy fed to the inverters pass through a board we realized with discrete components and, consequently, other causes of asymmetry come from this.
c. When the relay switches energy goes to the input of the second inverter. For about 40 seconds we don't see any changes in the output characteristic of this inverter but the output wattmeter measures a negative even if extremely low power flowing from the grid into the inverter. After 40 seconds, there is a negative peak of power, an almost constant absorption of power from the grid about -2,6W and then, finally, the inverter starts to inject energy into the grid.
   The low resolution of the wattmeter doesn't show the 40 peaks of synchronization we have introduced earlier in this chapter so it is not possible to see them on the characteristic of the wattmeter shown in figure 4.13 but it is possible to see it using an oscilloscope like in figure 4.11.

In order to avoid a waste of energy for eighty seconds we decided to take into account the problem of synchronization of the inverters and we solve it using a relay, an auxiliary generator and a software control.

The control is done through the following points:

1. Measurement of the maximum power variation over a time interval ΔT.
2. Calculation of so called "warm-up power limits".
3. Continue comparisons of the instant power with the power limits and consequent control of the relays on the board.

The first info gives us the maximum variation of power over a given time interval ΔT. Knowing this value and given the power limits for reconfiguration, ΔT and the 80s needed for the synchronization, we can calculate a power threshold to command the synchronization of the second inverter using an auxiliary generator.

For example, let's say that the power is increasing starting from a low value. When the power value reaches the limit of "warm-up start", the relay switches and the inverter is connected to the auxiliary generator from where it can take the energy needed for the synchronization task. Since we have considered the maximum possible power variation ΔPmax over ΔT, increasing the power, for sure after 80s or more, when the reconfiguration power limit will be reached, the inverter will be already synchronized.
This simplifies the solution of the problem and certainly it is not the best solution in terms of energy because we have considered ΔPmax, which is certainly bigger that the real ΔP involved; the consequence is that the inverter will be synchronized longer before the reconfiguration power limit will be reached. Certainly better solution can be find if the system will be commercialized but, for the experiments we want to perform during this thesis, our only concern is to guarantee the synchronization of the inverter when needed.

For the same reason of above, the system we are using will not disconnect the inverter completely when we consider the dual situation: when the inverter must be disconnected because the power limit of division has been reached, we will connect it to the auxiliary generator again. The reason is quite simple, if we completely disconnect the inverter it will lose its synchronization in a very short time and, if the power suddenly increases again, we might find the inverter not synchronized and not enough time for a new synchronization before switching. According to the points mentioned above, we calculate a second value of power called "warm-up stop" which represents the limit under which we can disconnect the inverter completely because even if the power will start increasing again, in any case, there will be enough time to start the warm-up procedure again, without risks that the inverter is not synchronized.

For a commercial system it would be interesting to create an algorithm that, based on continuous measurement of the power calculates, instant by instant, the value of ΔP and adjust the warm-up power limits automatically, adapting them in a way that the time in which the inverter takes energy from the auxiliary generator is reduced to that strictly necessary for the synchronization.

4.2.6.3 Auxiliary Generator – Choice of Power

When we decided to use the auxiliary generator, in order to guarantee an immediate working characteristic for the second inverter, we had to understand what kind of generator to use in order to accomplish this task. Of course a powerful generator makes certainly the work but at what costs? During the synchronization the absorption of power from the auxiliary generator into the second inverter is quite small as we can see but once this phase has finished the inverter is fully working and as much input energy we supply so much it will be converted. We are, therefore, getting energy from the grid through the auxiliary generator, supplying it to the inverter which converts it again in energy for the grid. Efficiency of conversion for both generator and inverter can be high but never one so this implies that we are spending energy to keep the second inverter synchronized.

How to limit the costs in terms of energy?

We experimentally tested this particular inverter to understand what are the limits of voltage and current, and hence power, to feed in order to guarantee the synchronization.
We found out that for these inverters the limits are 95V and 0,7A that corresponds to 66,5W. Interesting is the value of the voltage: in order to start the synchronization, the voltage value must exceed the U_{PV_start} value limit!

We have a power limit but not the energy cost yet since we must consider for how long the auxiliary generator will be physically connected to the inverter.

For our experiments we decided to raise the limit of voltage and current to 100V and 0,1A.

The software of control we realized has been build considering the following steps:

1. Turn on of the synchronization algorithm once the turn-on power threshold has been reached.
2. Keep the inverter synchronized till the switching power limit is crossed and the relay separates the generators or the power decreases under the turn-on power limit and, consequently, the synchronization task is aborted.

Through experiments we estimated with a rule of thumb that the time spent to keep the inverter synchronized is between tens of seconds and few minutes.

For every ten seconds while we keep the second inverter synchronized we spend 100J of energy so the option of guaranteeing the second inverter already synchronized when needed it is not cost free.
It is necessary to understand if the total energy gain using this system is finally attractive or not.

The experiments we have been able to realize with the laboratory equipment we have are involving levels of power really low. The maximum is 1,2KW but we didn't go much higher than a half of it.
From our calculation the power level at which the relay must separate the generators is about 330W. For simplicity of calculation let's suppose that this power is reached with 100V and 3,3A. At the moment in which generators divide each inverter receive at its input a power of 330/2W (165W).
The energy that we are losing when the second inverter is not already synchronized corresponds to 165W*80s=13,2kJ.

Let's consider this value of energy and an auxiliary generator which maximum output power is fixed at 10W (100V and 0,1A). We want to calculate for how long the inverter must be synchronized, connected to the auxiliary generator and not to the PV generator, to spend the same amount of energy that we would gain during the 80s with the inverter already synchronized: $\frac{13200J}{10W} = 1320s$.

We are not considering the losses of the auxiliary generator, of course, but these numbers give us enough interesting results to come to the conclusions that:

1. The synchronization of the second inverter isn't energy free;
2. It is necessary to supply energy to the inverter before the power limit of separation is reached, this implies the need of an auxiliary source of energy that could be the grid itself through an external device;
3. It is necessary hardware to measure the variation of power (already included in commercial inverters) and software to decide when the inverter must be connected to the auxiliary source;
4. Once the maximum power out of the auxiliary source has been chosen, the energy costs to keep the inverter synchronized are closely related to the quality of the software since less time the inverter will be synchronized but on hold, less energy will be finally wasted for the whole synchronization process.

The software of control we have developed allows us to experiment and verify the hypothesis at the basis of the TEAM system concepts but we are aware of possible future improvements that can be done on it, making it more efficient and, consequently, making the whole system more efficient allowing higher energy gain. One for all, developing a better algorithm for deciding the turn-on power threshold would already imply higher efficiency in terms of reduced power losses.

4.2.7 The Wattmeter

The instrument that allows us to understand what is the behaviour of the inverters at their output is the wattmeter. For this experiment we used a Wattmeter Yokogawa WT1600 which measures, among many options, current, voltage and power of the inverter at their output when connected to the grid.

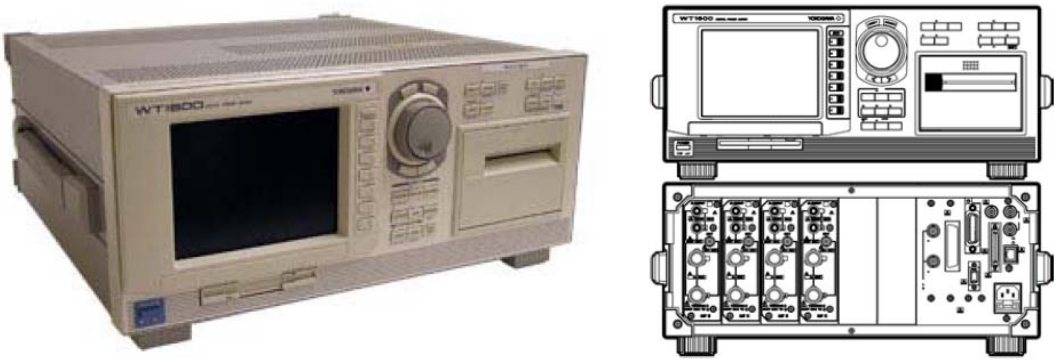

Fig. 4.14 Yokogawa WT1600 wattmeter.

4.2.8 Instruments of General Use

Making these experiments in a laboratory we have been using instruments as an oscilloscope for understanding the behaviour of some characteristics and a power supply for supplying energy to the active elements used for the control and the measurements on the control board.

An Agilent DC generator of 130V maximum output voltage has been used as auxiliary generator for the synchronization of the inverters.

4.3 Results

The object of this thesis is to verify if it is possible to inject into the grid more energy using a dynamic system or a static one considering the fact that the curve of the efficiency of the inverters is usually low when the energy supplied from the PV generators to the input of the inverters isn't high enough. With a reconfigurable system we believe that modifying in real time the connection of the generators with the inverters when the power supplied is low, we can achieve better results in terms of injected energy.

What we will do, therefore, is to consider the same system and the same curve of power supplying the inverters first with a static configuration and then with a dynamic one.

We will graphically show the results and we will calculate how much energy we are able to inject into the grid in each case and for each curve of power considered.

4.3.1 Original Curves and Supplied Curves

Considering the characteristics of the original curves we want to use for the experiments and those that effectively we can supply to the inverters or those measured through the wattmeter, the first important detail that we immediately see is a huge difference between the original curve and the others.

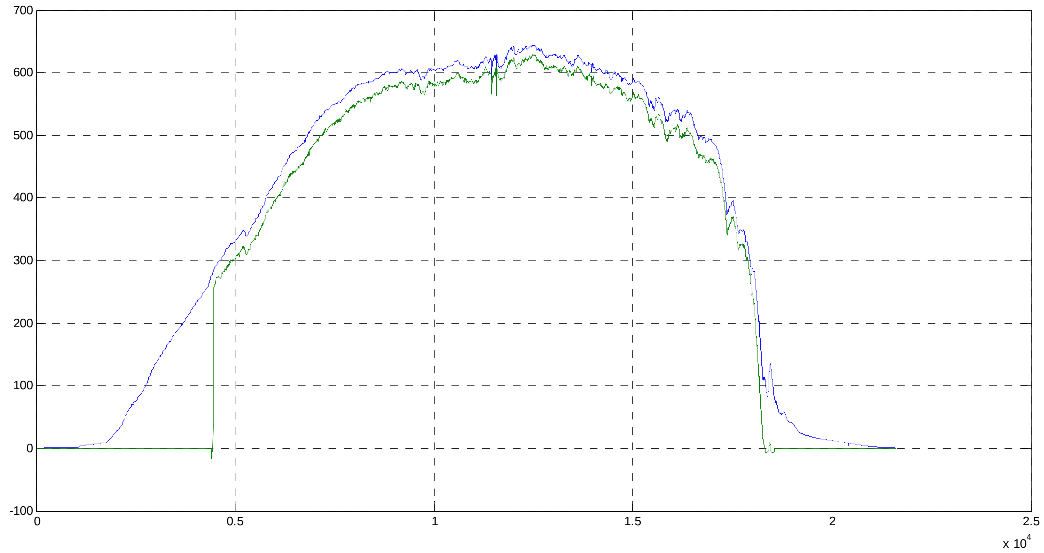

Fig. 4.15 Original sunny curve vs. static output.

In figure 4.15 we show the original curve for the sunny day characteristic (blue) and the output curve measured from the wattmeter (green) when the system is configured with a static design. The fact that the green curve is down-shifted respect to the other is a normal consequence of the sum of the losses that the system introduced along the conversion of the energy.

What is more interesting is the shape of the green curve. We notice a very step characteristic at the beginning and a less but still evident down-step at the end of the static output characteristic.

The explanation for such behavior is strictly related to the characteristic of the inverters.
As earlier mentioned the inverter Sunny-Boy 700 is characterized from a U_{PV_start} value of 95V and a MPP range [75÷150]V. At the beginning, until the input voltage reaches a value of 95V (almost open circuit), the inverter doesn't allow any flow of energy go through to the grid; once this value has been reached and after the 80 seconds of synchronization, the inverter starts to inject energy and the result is the steep slope we see in the figure.

The current characteristic follows closely the power characteristic while more interesting is to look at the voltage characteristic in figure 4.16.

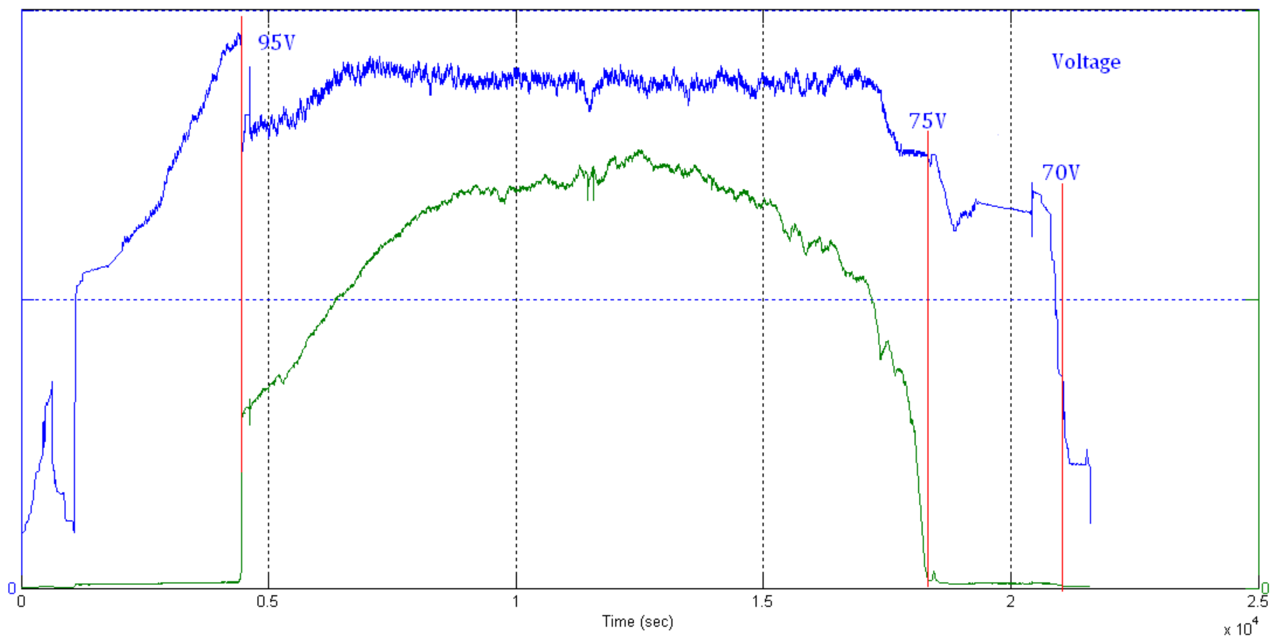

Fig. 4.16 Power vs. voltage characteristics at the input of the inverter for a static system.

In figure 4.16 we can better see the connection between power variations and voltage variations. First of all, as we said, as long as the input voltage of the inverter doesn't reach the 95V limit, no energy flows through the inverter, it only absorb energy from the generators and from the grid but a very small quantity.

The green power characteristic isn't the power characteristic at the output of the inverter but at its input and shows how much power is being supplied to the inverter: negligible.
Once the 95V limit has been crossed, the inverter starts to work in the MPP mode, the voltage decreases while the current increases and the system moves toward the maximum power point for maximizing the energy conversion efficiency.
As long as the power has a voltage component inside the MPP voltage range the inverter is capable of seeking for this point of "best conversion" but, once the lower limit is reached (75V), the inverter stops working in MPP mode and converts as best as it can the energy received from the generators, in other words, the conversion happens with low efficiency.
Finally, when the threshold limit of 70V is crossed the inverter stops injecting energy into the grid. From some experiments aimed to understand its behavior under switching circumstances it seems like it loses the synchronization with the grid, no energy can flow unless the 95V limit is crossed again.

4.3.2 Sunny and Cloudy Tests

In figure 4.16 we have shown the curve representing the database for a sunny day and we also show, of this curve, what is the curve of power that we are finally able to supply to the inverters and hence the energy injected in the grid.

From now on we will show and comment the curves that we registered through the wattmeter at the output of the inverters unless differently specified.

4.3.2.1 Sunny Curves: Static vs. TEAM

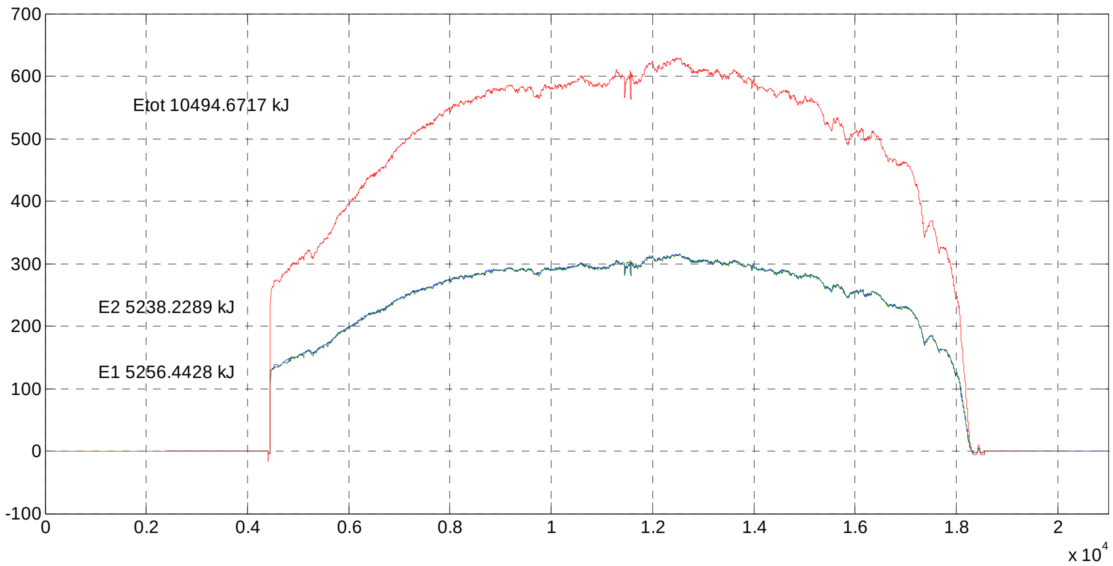

Fig. 4.17 Sunny curve output with static design

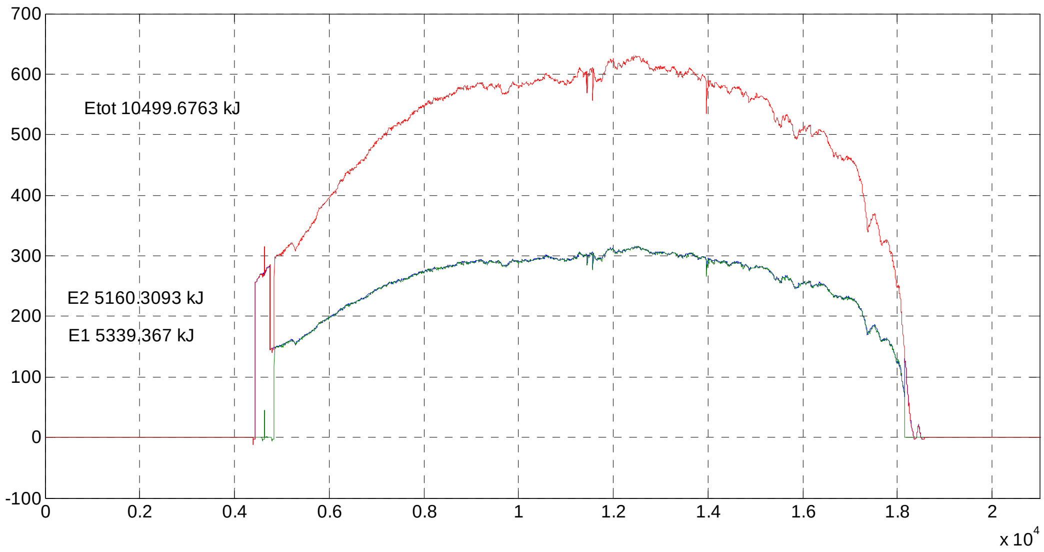

Fig 4.18 Sunny curve output with TEAM design without auxiliary generator

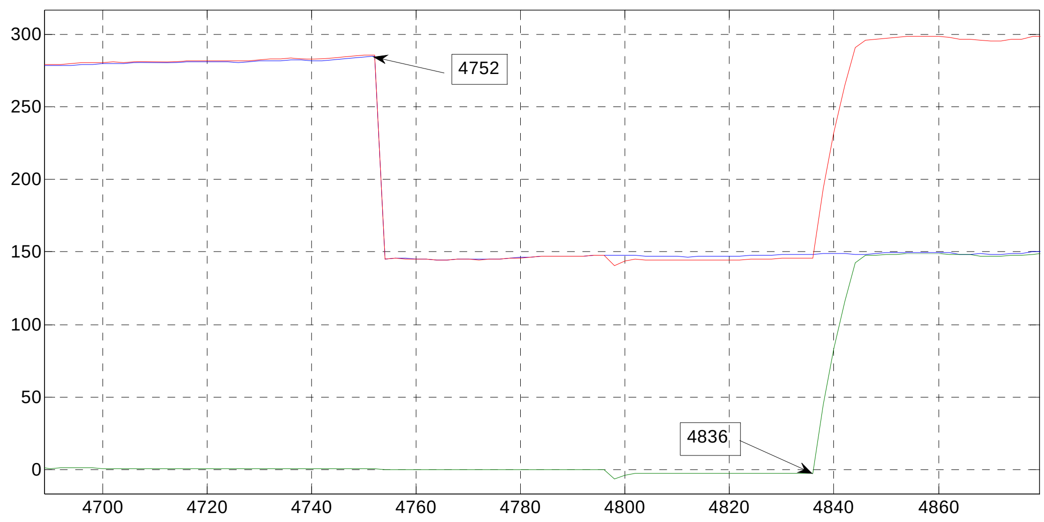

Fig. 4.19 Sunny curve output with TEAM design without auxiliary generator – Zoom

In figure 4.19 we see the effects of the second inverter not synchronized when the relay switches opening the generators. Between the moment in which the relay switches till the moment in which the second inverter starts injecting energy in the grid there is an 84 seconds gap of missing energy.

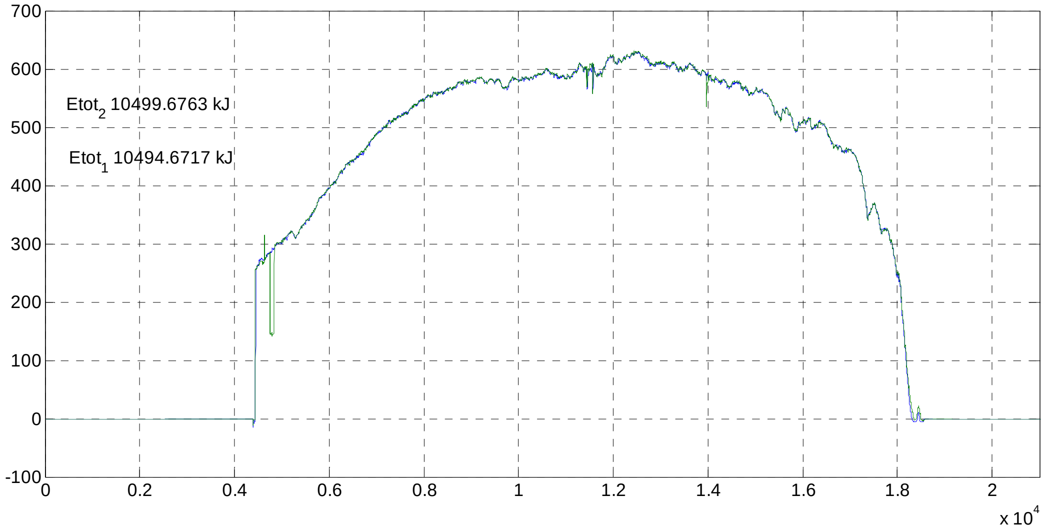

Fig. 4.20 TEAM design without auxiliary generator vs. static design

Considering the difference between static design and TEAM design without auxiliary generator we measure a difference of energy of 5kJ which corresponds to an improvement of injected energy equal to 0.048% respect to the energy injected with the static design.

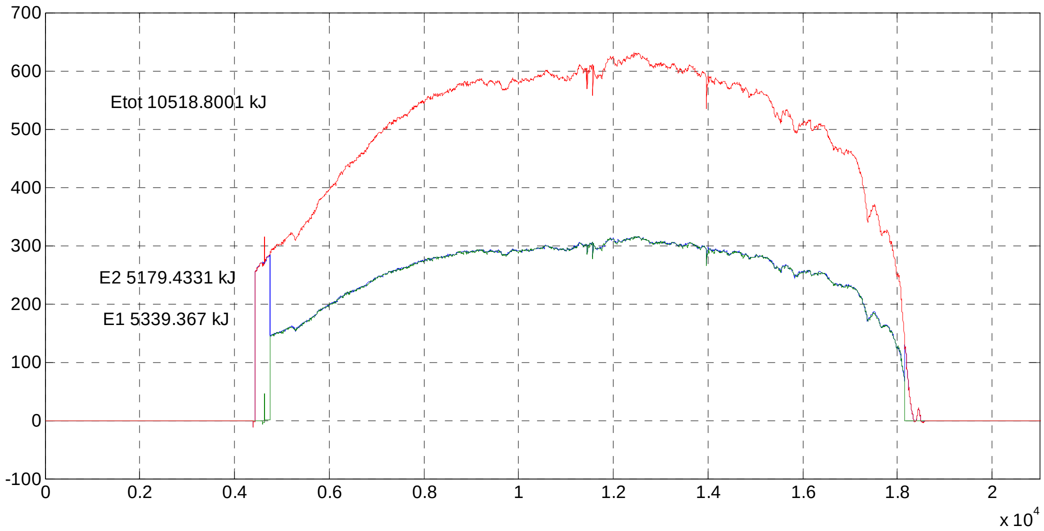

Fig. 4.21 Sunny curve output with TEAM design with auxiliary generator

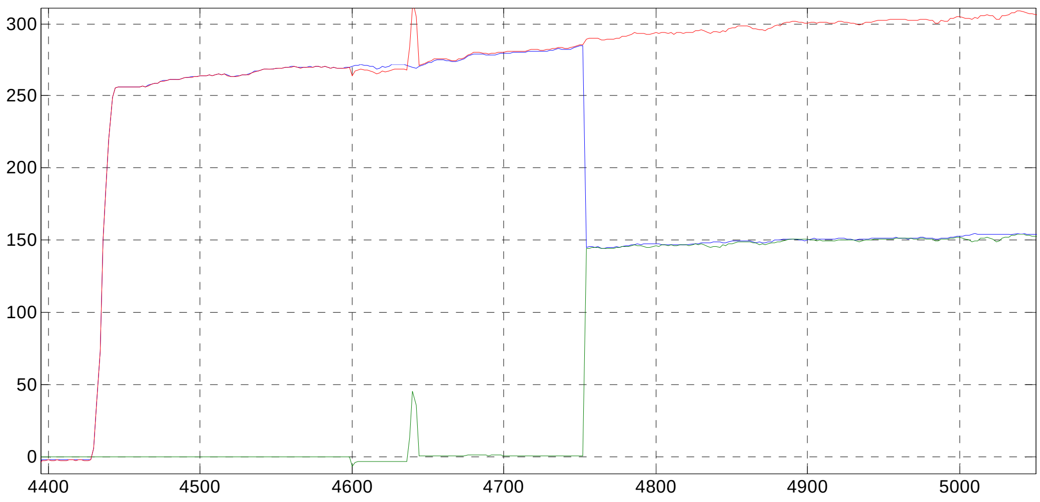

Fig. 4.22 Sunny curve output with TEAM design with auxiliary generator – Zoom

We see from figure 4.22 that using an auxiliary generator we can avoid the problem of the synchronization of the second inverter.

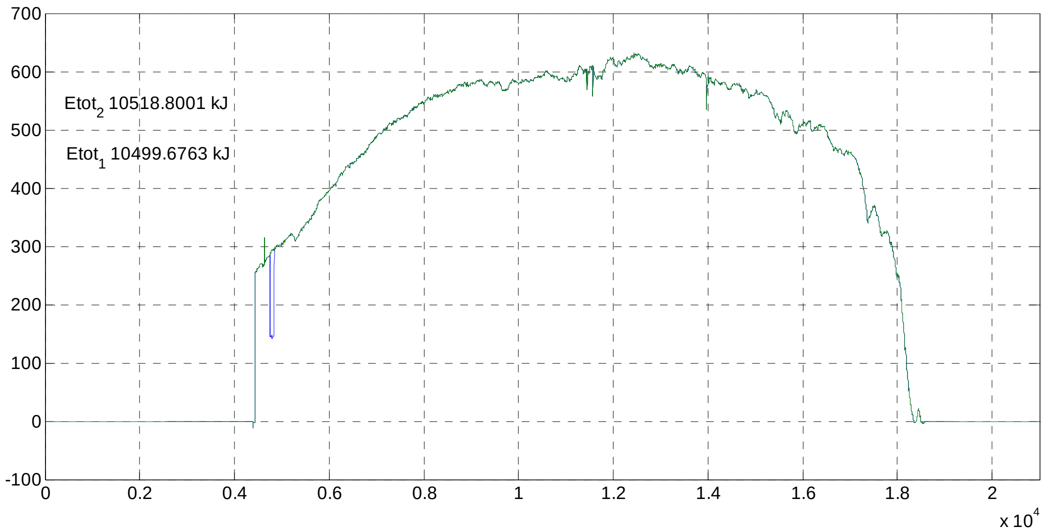

Fig. 4.23 TEAM design with auxiliary generator vs. TEAM design without auxiliary generator

Improving the TEAM system with an auxiliary generator we measure a higher energy injected equal to 19kJ which corresponds to an improvement of the energy injected equal to 0.18% respect to the whole energy injected with the TEAM design without auxiliary generator.

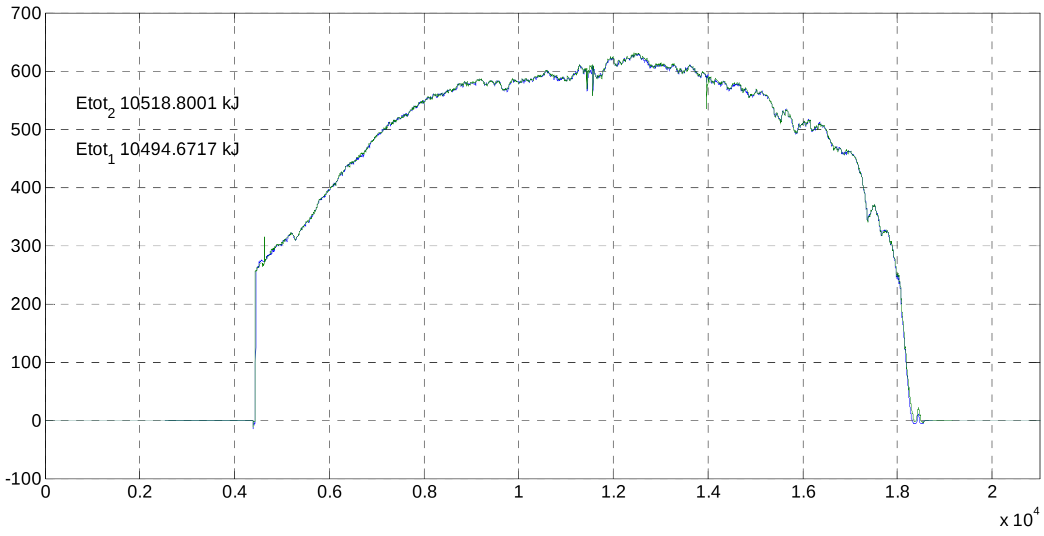

Fig. 4.24 TEAM design with auxiliary generator vs. static design

We can finally quantify how much total improvements we reach with a TEAM design using an auxiliary generator in respect to the static system.

The difference of energy is 24kJ which corresponds to an improvement of 0.23% respect to the whole energy injected with the static system.

4.3.2.2 Cloudy Curves: Static vs. TEAM

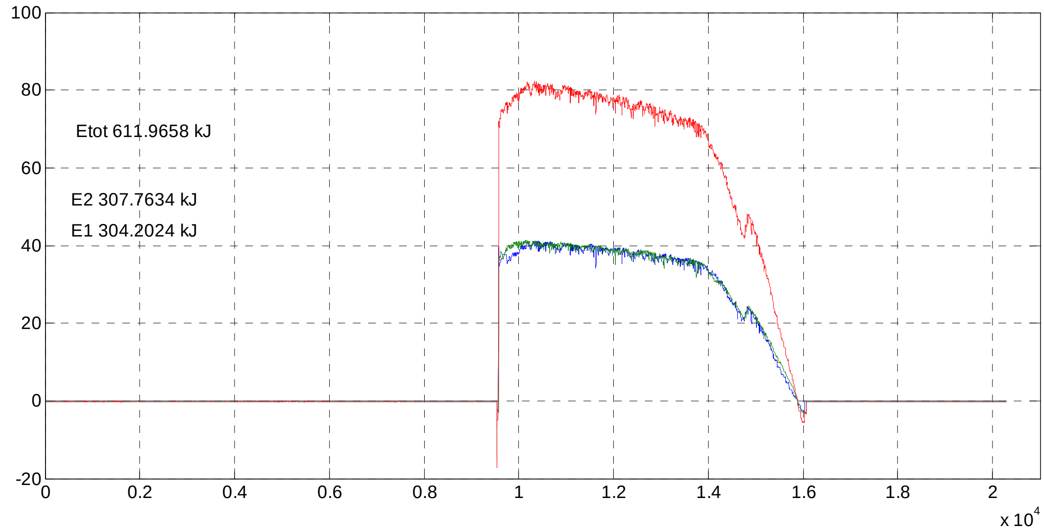

Fig. 4.25 Cloudy curve output with static design

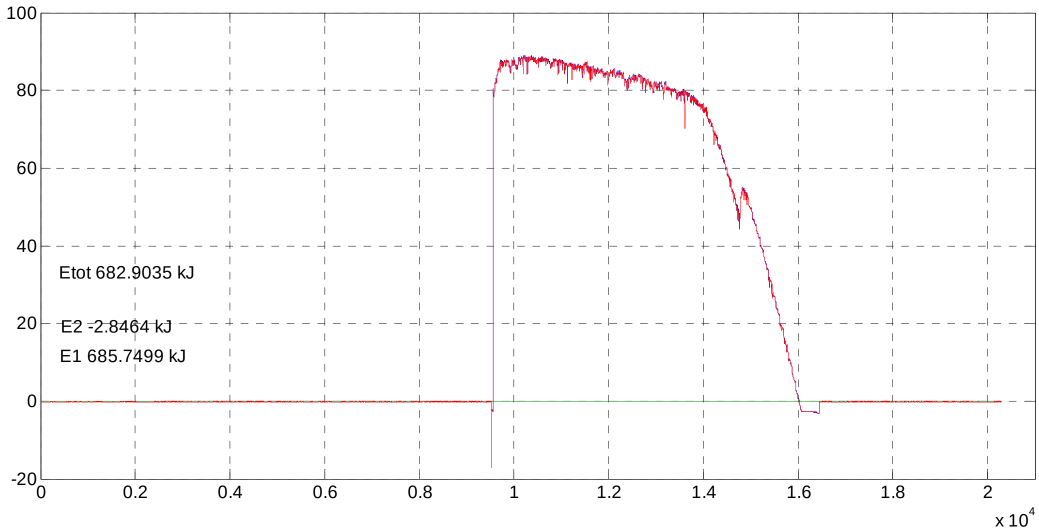

Fig 4.26 Cloudy curve output with TEAM design and auxiliary generator

This curve is really interesting: for a cloudy day in which the level of energy produced through the solar panel are quite low we see that the team system doesn't command a switch of the relay and for all day long only one inverter is involved into the conversion of the energy.

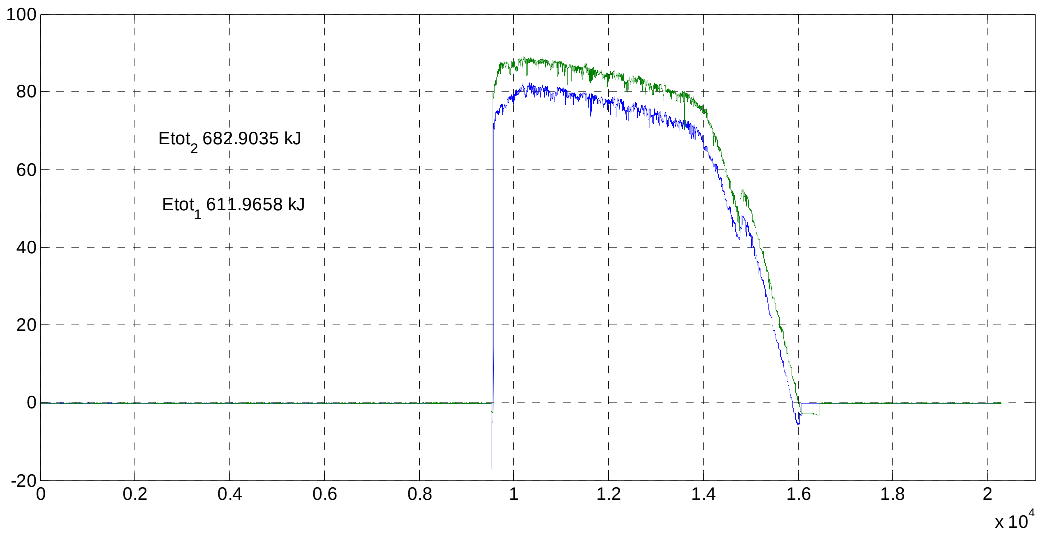

Fig. 4.27 TEAM design with auxiliary generator vs. static design

As expected we see in figure 4.27 a big difference between the curve of the TEAM system compared with the static design. The reason is, as mentioned earlier, strictly related to the amount of energy flowing from the generators into the inverters. We said that the curve of the efficiency for an inverter shows a low efficiency when the incoming energy into the inverter isn't high enough. Modifying the sizing factor we improve this curve of efficiency because connecting two generators to only one inverter we double the amount of incoming energy into this inverter while the other one stay disconnected.

Finally the improvements in terms of energy between TEAM and static design for a cloudy day are 70.9kJ which corresponds to 11.6% of the whole energy produced with static design.

4.4 Conclusions

The results so far collected allow us to draw some conclusions:

1. Even using a very small PV installation like the one we have been able to simulate into our laboratory we can already achieve efficiency improvements using the TEAM design compared with the static design of a PV system.
2. A cloudy day in which the power we collect from the sun is so low that the division power limit is not even reached and the generators keep supplying only one inverter is the best case to show the utility of the TEAM design because the system works all day long with only one sizing factor and only one inverter is connected.
3. During a sunny day, having only one inverter connected during the hours of the morning and of the evening in which the power is low still gives us an efficiency improvement using the TEAM design because, changing the sizing factor, again the system auto-configures to situations of low power injection and so increasing the efficiency of the inverter and hence the efficiency of the whole system.
4. We can certainly affirm that the best results come from the cloudy day experiment but this is something that we expected since the reconfiguration and, therefore, the TEAM concept is most efficient when there is low power injected into the inverters, once the inverters are separated, in fact, the system configuration of TEAM and static system is identical and identical results are expected.
   Only when the generators are connected we expect a difference.
5. There are certainly more experiments and studies to do about the difference between static and TEAM design but two points must be taken into account:
   a. The hardware needed to realize the TEAM system is already partially included into the inverters themselves since they give information about power, voltage, energy and so on. The hardware missing is made of few relays and a simple control which can be realized and integrate into the inverters themselves making the costs of it extremely cheap for the constructors.
   b. If the PV installation is so little that one inverter is enough to convert the energy self-produced then there is no sense to buy two inverters to step to the TEAM design but, unless we are talking about toy PV system, usually more inverters are always necessary and if with two inverters we already achieve improvements of the efficiency, better improvement can be reached with more inverters

and without extra not necessary costs because more inverters are already needed.

5 CHALLENGING THE U_{PV_START} THRESHOLD

5.1 Introduction

From the datasheet of SMA Sunny Boy / Sunny Mini Central – Operating Parameters (page 13) [7] "U_{PV_start} (V_{PV_start}): the DC voltage required before the inverter begins feeding power into the grid. This value is about the minimum MPP voltage which is required in order to guarantee safe connection to the grid and to minimize grid relay wear".

After a recall on what this value physically mean we want to show what effects it introduces and what improvement we might obtain by forcing it to change.

5.2 U_{PV_start} Threshold

In previous chapter we have shown the following image:

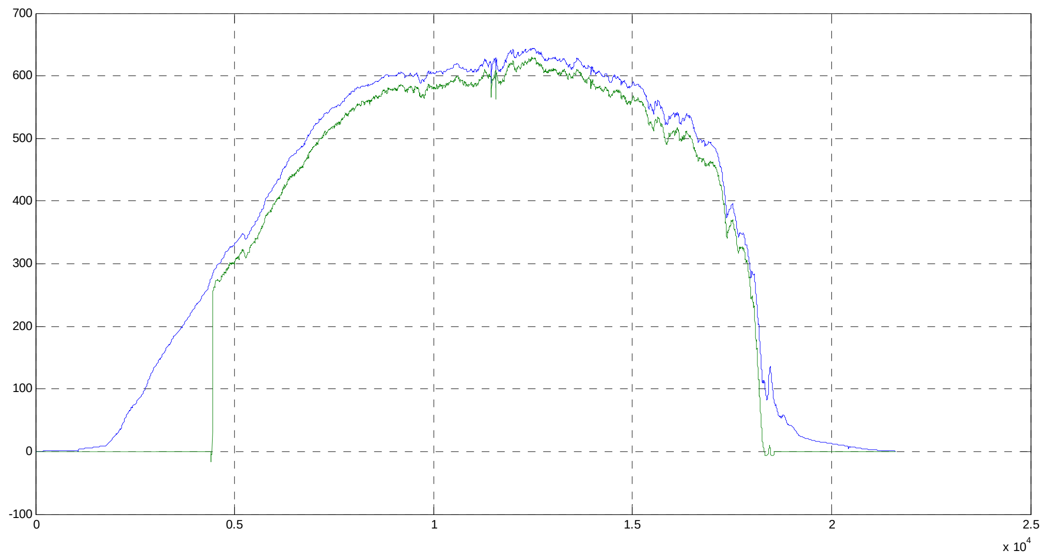

Fig. 5.1 Original sunny curve vs. static output.

We have also explained that the output curve measured from the wattmeter (green) has this shape because of a value called U_{PV_start} which is the voltage threshold to cross in order to see the inverter passing from a stand-by state to an operative state.

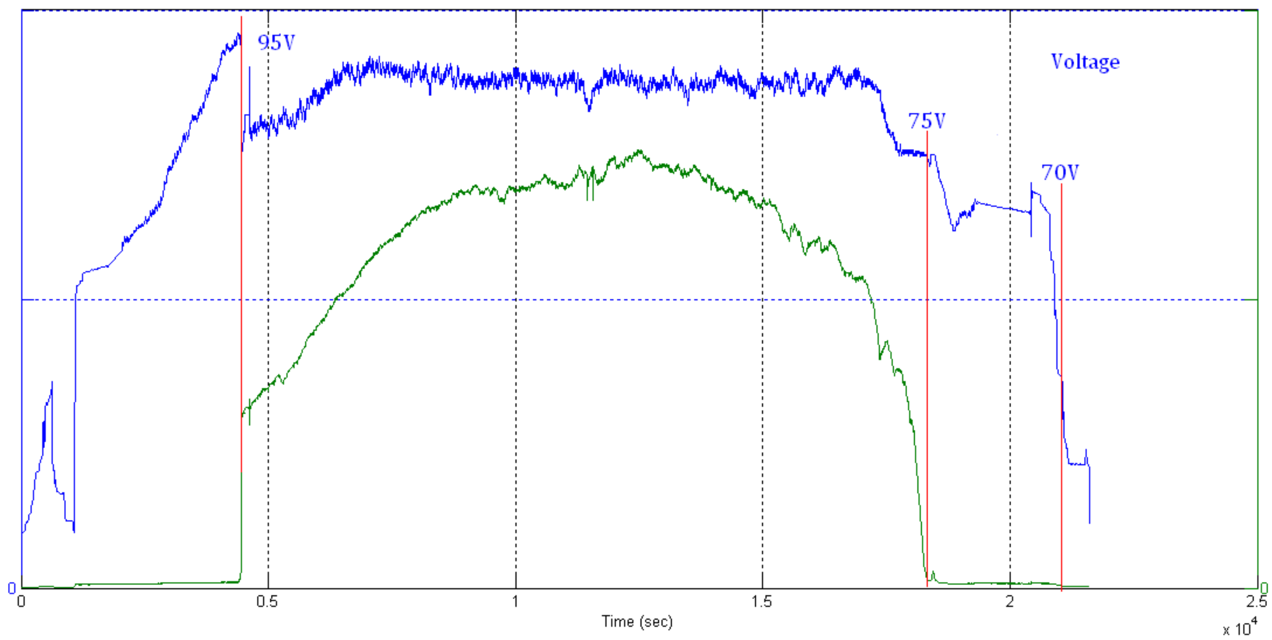

Fig. 5.2 Power vs. voltage characteristics at the input of the inverter for a static system.

Again in figure 5.2 we show the relation between power and voltage for a sunny curve in order to underline the strict connecting between the characteristics.

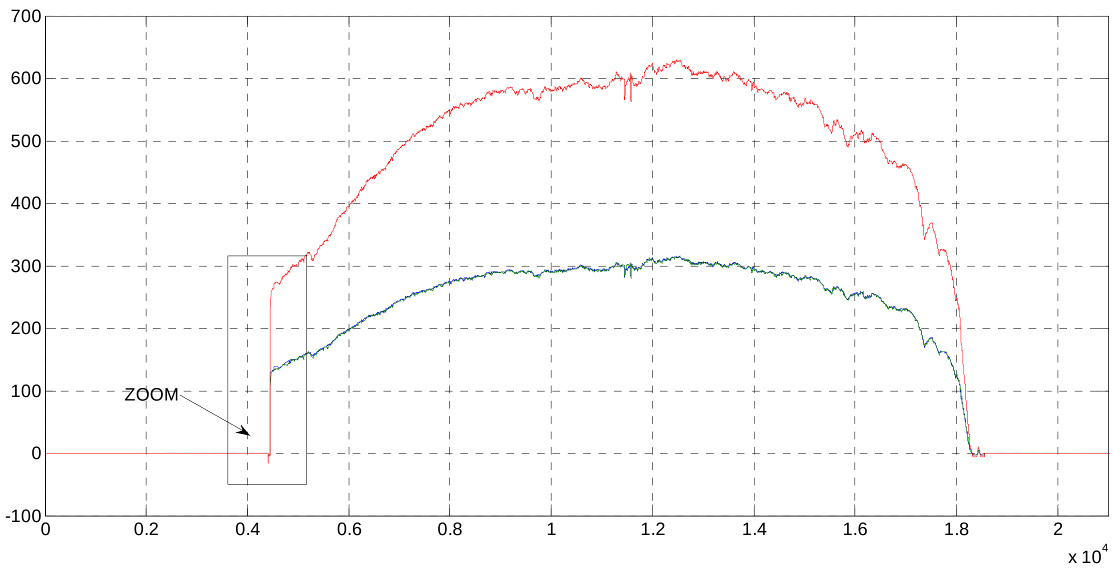

Fig. 5.3 Sunny curve with static design

As long as the voltage of the input characteristic doesn't reach this threshold limit we have noticed that the SAS generator works with almost open voltage values, the amount of current we can supply is quite low, the inverter isn't active and, actually, it absorbs an average power of few mW from the grid.

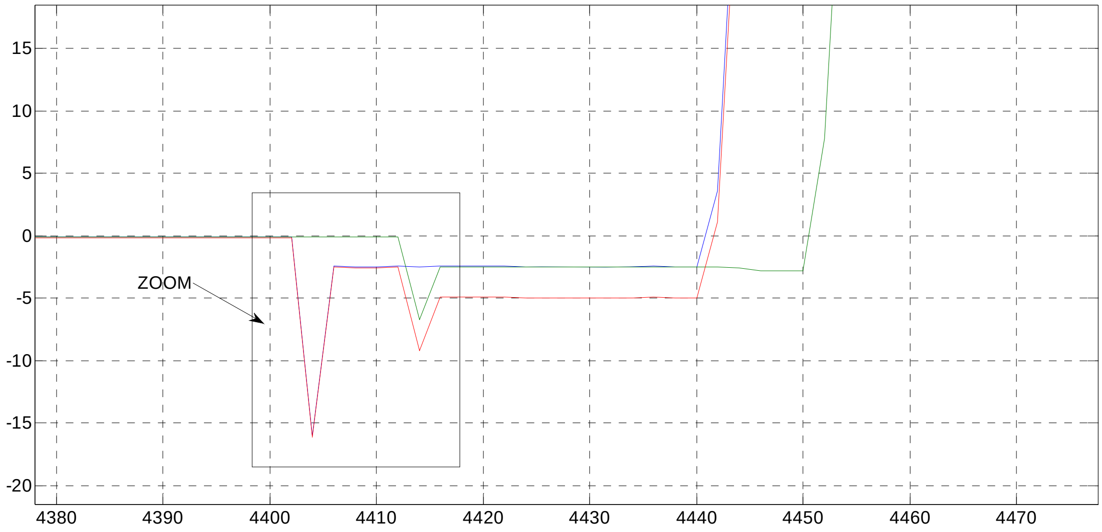

Fig. 5.4 Sunny curve with static design - zoom

Once it starts synchronizing it absorb small quantity of energy from both the generators and the grid.

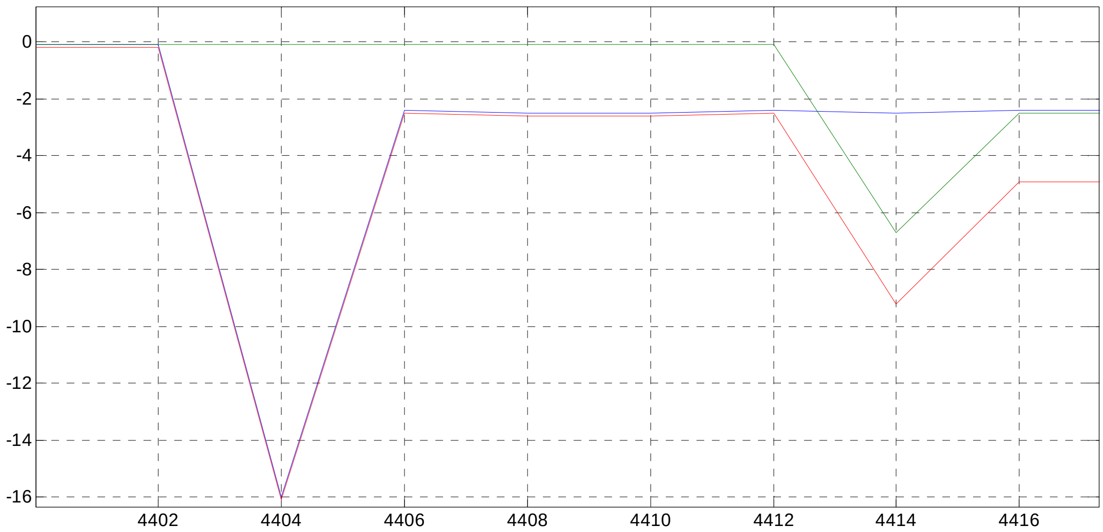

Fig. 5.5 Sunny curve with static design - zoom

In figure 5.5 we see a zoomed area of the characteristic measured with the wattmeter: a peak of negative power (negative means energy absorbed from the grid) and then an average absorption of energy -2.6W for each inverter till the moment they become operative and supply energy from the generators to the grid.

Once the open circuit voltage of the generator reaches the U_{PV_start} threshold limit the inverter will start its synchronization, then will become operative and will start searching for the maximum power point, consequently the voltage we see on the SAS and from the characteristics will fall down while the current will rise up and both quantities will be adjusted in a certain amount of time at the values of the maximum power point.

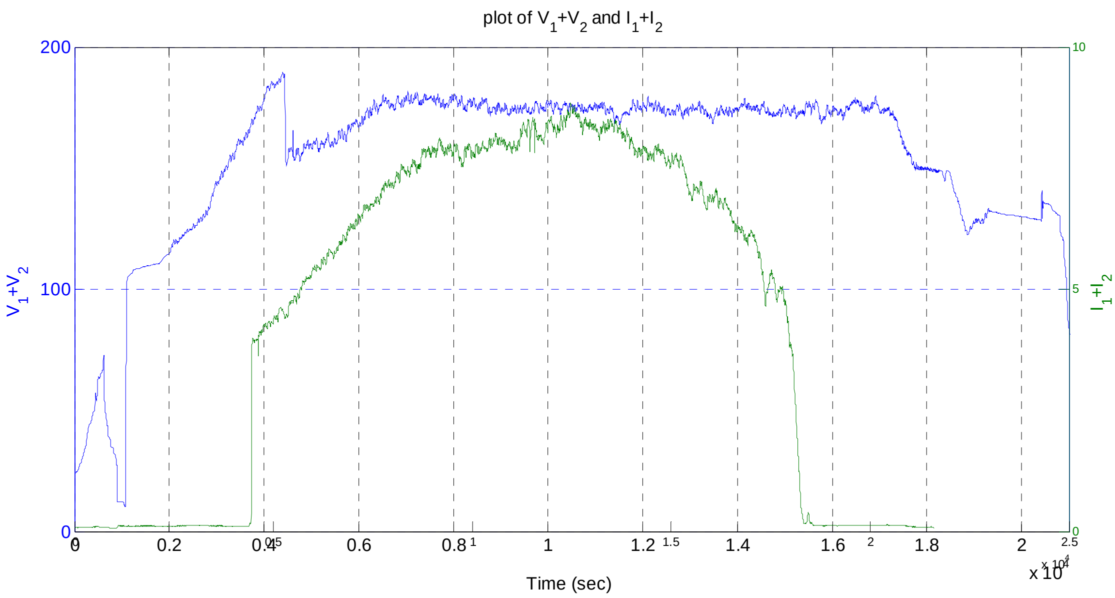

Fig. 5.6 Sunny curve – voltage and current.

As we can see from figure 5.6 and considering previous curves, we notice that the shape of the current curve is very similar to the shape of the power curve, most important, as well as the power, also the current starts showing relevant values only once the U_{PV_start} limit is crossed.

We notice also that while the inverters are not operative a little but continuous flow of current of small entity flows from the generators into the inverters while, at the output, the wattmeter shows us an extremely little value of negative current. This means that the little energy related with the current coming from both generators and grid is all lost inside the inverters.

5.3 Lowering U_{PV_start} Limit

The Sunny-Boy 700 used for this experiments have a MPPT range of [75 – 150]V which means that as long as the voltage of the power curve has a voltage value included in this range, the inverter algorithm is able to search for the maximum power point but, since the U_{PV_start} threshold is 95V, the inverter will be not be operative and hence will not be injecting any energy at all into the grid as long as the voltage value doesn't reach this limit.

In order to make the inverter two already synchronized when the power limit was reached and generators divided, we have previously automatically connected it to an external generator with 100V and 0.1A (10W) in order to synchronize it and keep it synchronized as long as needed.

Let's use the same auxiliary generator also on the first inverter!

We decided to use the same generator also to control a synchronization of the first inverter for voltage values below the 95V open circuit voltage limit.

When the open-circuit voltage of the generators reach a certain value we connect the first inverter to the auxiliary generator till it gets synchronized, then, we connect it back to the SAS generator. The state of the inverter at this point is related to the value of open circuit voltage that we have chosen when we started the synchronization:

1. If the open voltage value was above 82V, the inverter, once reconnected to the SAS, find its operative power point at Vmp=75V or more and, consequently, its state will be synchronized and operative;
2. Otherwise, if the voltage is under the 82V limit, after reconnecting the inverter to the SAS it loses the synchronization or keeps it without being operative; it depends on the Vmp value if it is above or below the 75V limit.

For this particular inverter we have experimentally quantified the difference between open circuit voltage of the inverter not synchronized and the inverter synchronized and operative in 7V.

The goal of the experiment was to oblige the inverter to start working before the U_{PV_start} voltage were reached and we made it.

The mentioned datasheet says that the U_{PV_start} "is above the minimum MPP voltage which is required in order to always guarantee safe connection to the grid and minimize grid relay wear"[7]. Well, since the minimum MPP value is 75V, considering as switching limit the value of the voltage open circuit, we guarantee that the inverter will be synchronized and operative for 75V or more.

5.4 Sunny and Cloudy Tests

We want to show the differences between the following cases:

- Static
- Static advanced (which means considering an anticipated start working point for both the inverters)
- TEAM with auxiliary generator
- TEAM advanced (with auxiliary generator used also to anticipate the start working point of the first inverter).

5.4.1 Sunny Curves: Static

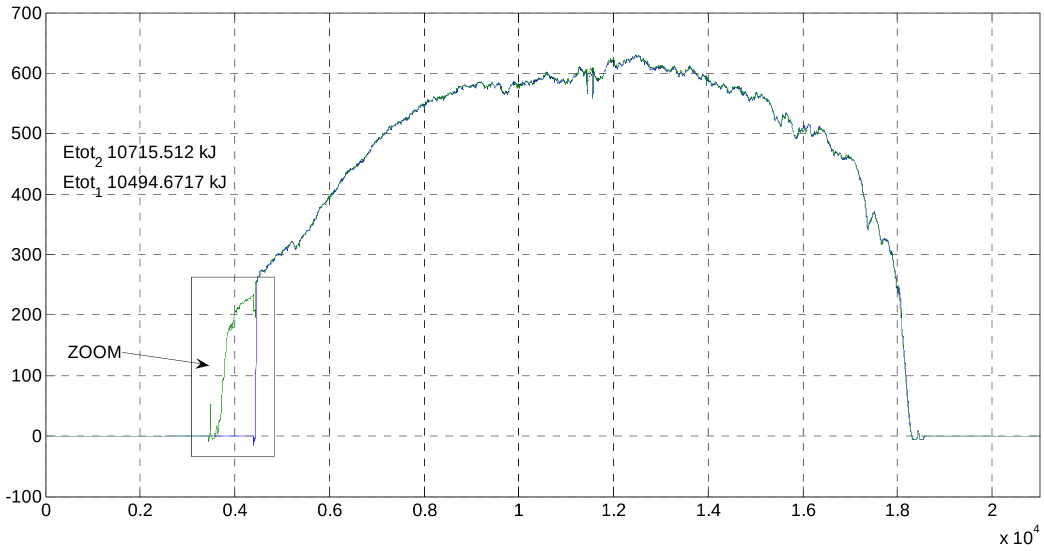

Fig. 5.7 Sunny curve output with static design: standard vs. advanced

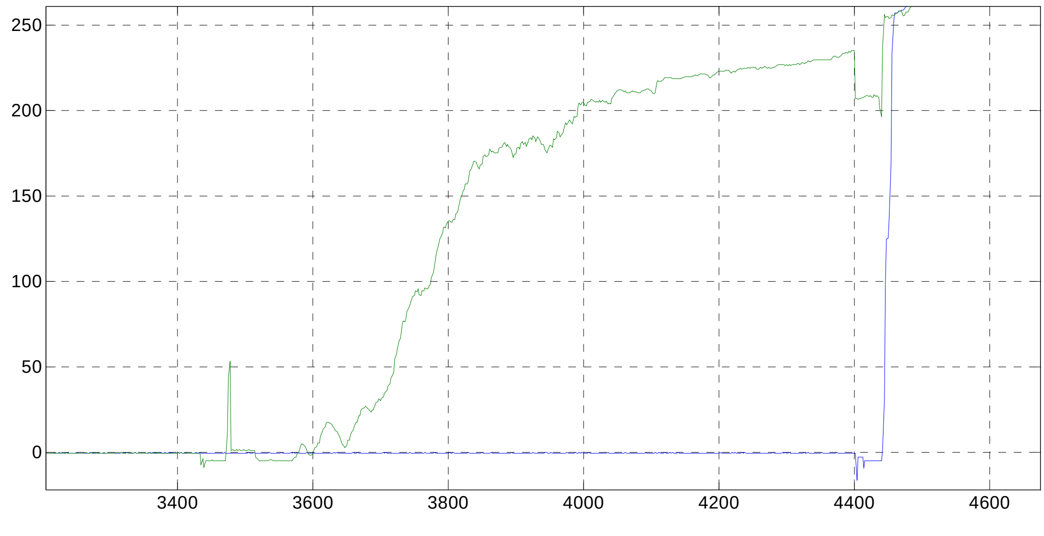

Fig. 5.8 Sunny curve output with static design: standard vs. advanced - zoom

From figure 5.8 we notice that forcing the first inverter to start being operative to a lower open-voltage threshold level we gain an amount of energy equal to the area between the two curves in the plot while the rest of them is identical because we are considering the static design where no alterations to the configuration of the system is done.

In terms of energy, forcing the inverters to start injecting energy with a lower open-circuit voltage threshold gives us extra 221kJ which corresponds to 2.1% extra energy respect to the static system “standard”.

5.4.2 Sunny Curves: TEAM

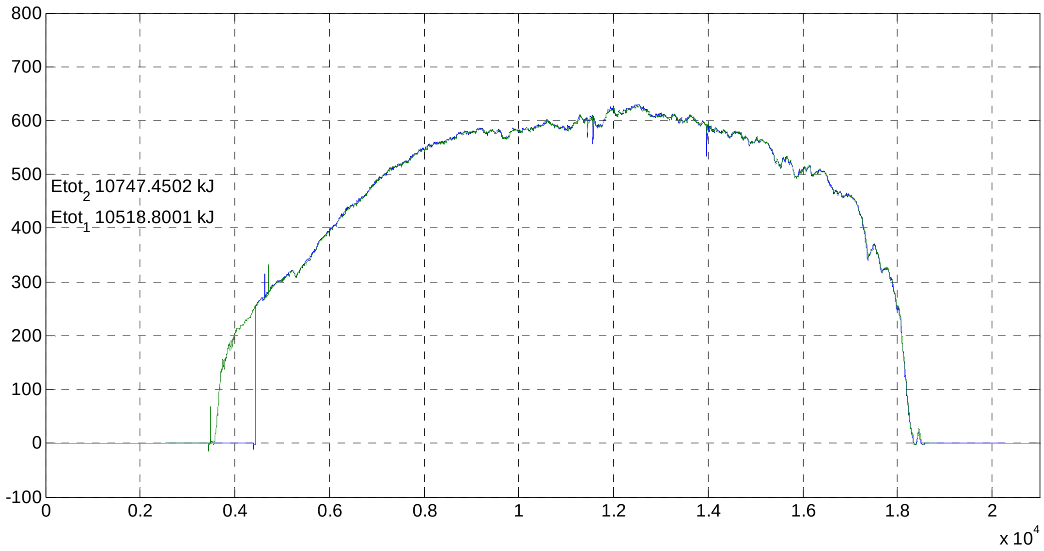

Fig. 5.9 Sunny curve output with team design: advanced vs. standard

Also in this case we see from figure 5.9 a huge difference of the curves at the beginning of the characteristic when the first inverter becomes operative; the rest of the curves are identical since the control commanding the division or association of the generators according to the TEAM system design in the same.

In terms of energy we have a gain of 229kJ which corresponds to a 2.17% of total energy improvement.

5.4.3 Sunny Curves: Static vs. TEAM advanced

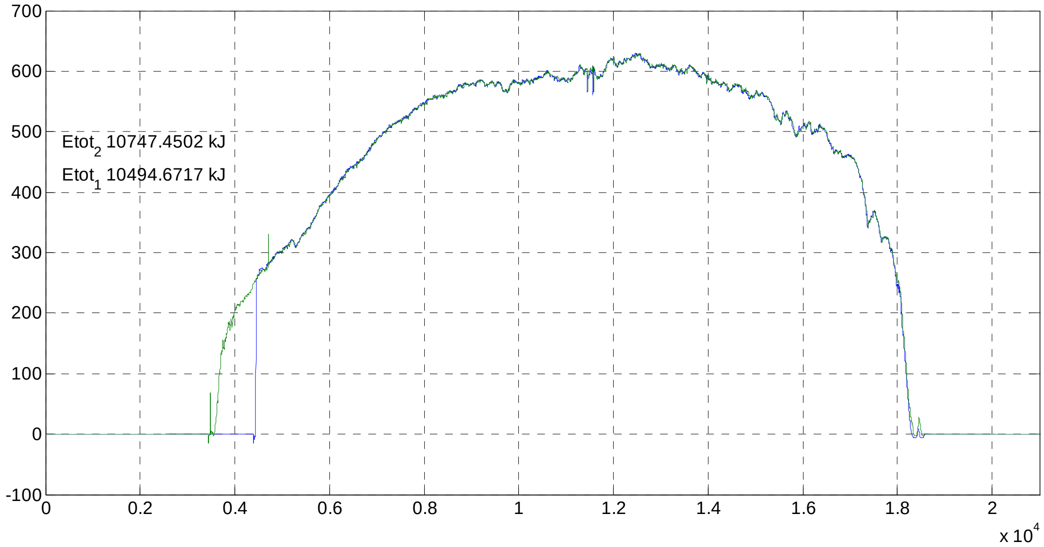

Fig. 5.10 Sunny curve output: static standard design vs. TEAM advanced design

With the figure 5.10 we show the final result along all the possible improvements we thought about within this thesis: a static standard system design compared with a dynamic TEAM design with an auxiliary generator used to force the first inverter to enter sooner into operative state.

The energy total gain is 253kJ which corresponds to a 2.4% extra energy compared with the total energy injected with the static design standard.

5.4.4 Cloudy Curves: Static

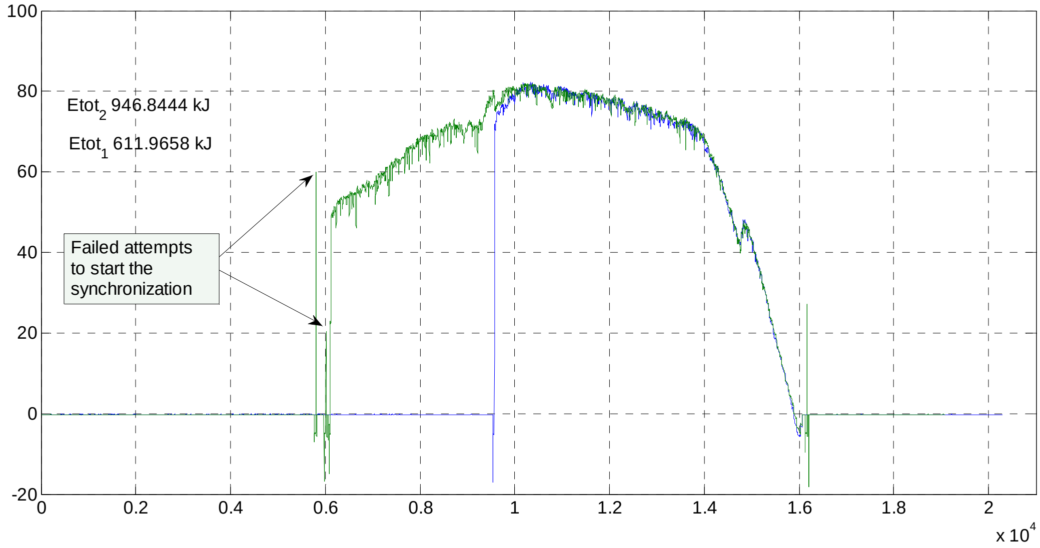

Fig. 5.11 Cloudy curve output with static design: advanced vs. standard

In figure 5.11 the cloudy output curves with static design are shown. Improvements are visible. Interesting is underlining those two peaks of power indicated by the arrows. They mean that the control tried twice to force the inverters into an operative state but, because of variations of voltage, the system failed to do so and new attempts have been made till it finally worked.

The energy improvement in this case is of 334.9kJ corresponding to the 54.7% of the total energy of the static standard design.

5.4.5 Cloudy Curves: TEAM

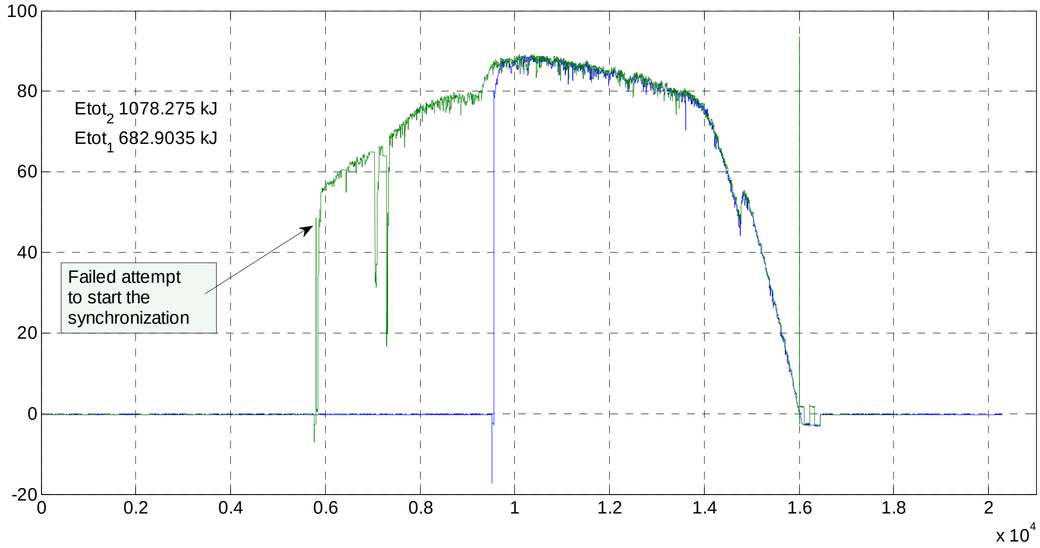

Fig. 5.12 Cloudy curve output with TEAM design: standard vs. advanced

TEAM design standard and TEAM design advanced, still we have huge improvements: 425kJ corresponding to a total energy gain of 62.6% respect to the total energy of the TEAM standard design.

5.4.6 Cloudy Curves: Static vs. TEAM advanced

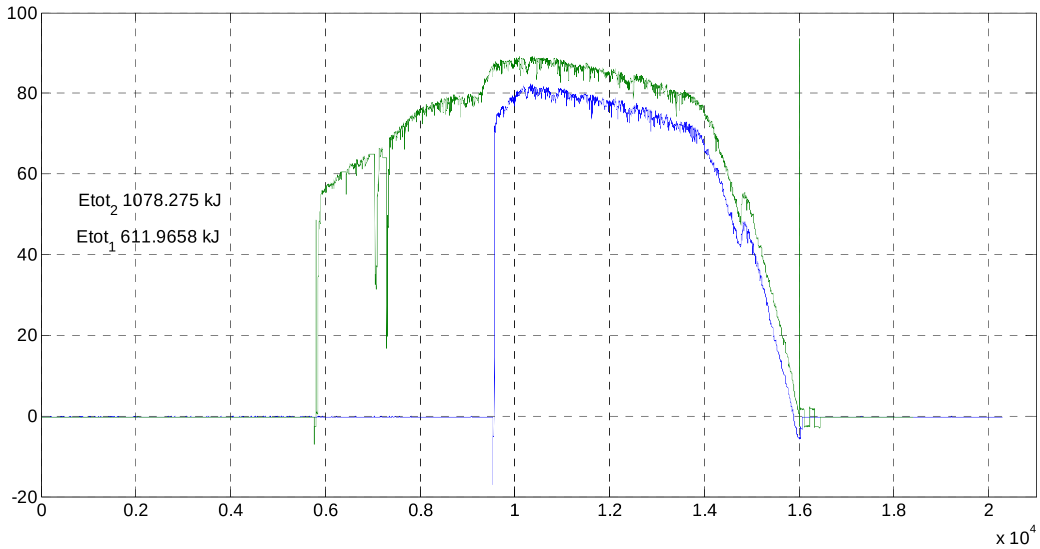

Fig. 5.13 Cloudy curve output: static design standard vs. TEAM advanced

The total improvement passing from a static standard design to the TEAM advanced design is of 466kJ corresponding to 76.2% of extra total energy injected into the grid.

5.5 Conclusions

Considering TEAM advanced design versus static standard device, the amount of extra energy we are able to inject into the grid is varying from a 2.4% for the sunny curves up to 76.2% for the cloudy curves considering, of course, the database we have used for the experiments.

The difference in the percentages is huge and needs an explanation.

As we said earlier, the TEAM system is mostly useful when the energy injected into the inverters is low and, hence, using this dynamic design, we force double energy into one inverter forcing it to work to a higher efficiency point of conversion until there is enough input energy to guarantee an operative working point with high efficiency.

For the cloudy curve of our experiments we have underlined that the characteristic has a so low level of power feeding the inverter that, when the TEAM design is applied to the system, the second inverter is never involved in the process of energy conversion, besides, we can also affirm that the inverter works all the time with a low efficiency operative point which is even worse when the static design is applied because the input power is divided by two and supplied to two inverters.
This consideration explains the big difference of improvements between the results between static and TEAM dynamic design.

What, instead, explain the huge difference of values between the gain with the sunny curve and that with cloudy one is the different total energy injected into the grid using the static system:

1. The total energy gain for the sunny curve is 253kJ but, considering that 10495kJ is the whole energy injected using a static standard design, the results in percentage correspond to a 2.4%;
2. The total energy with the sunny curves is 466kJ, which is not much higher compared with the gain of the sunny curve, but, in this case, the total energy injected with the static standard design is much lower, 612kJ, and hence the resulting percentage is much bigger, 76.2%

6 CONCLUSIONS AND FUTURE LINE OF INVESTIGATION

6.1 Introduction

Compared to the static design it is possible to improve the injected energy into the grid adopting a dynamic design.

- With the TEAM system we demonstrate that reconfiguring the system dynamically in order to inject the energy fed by the generators in only one inverter instead of sharing it among all the inverter connected to the generators allows the inverter involved to work with a better efficiency point of conversion.
- The percentage of improvements is strictly related to the characteristics of the curve of power supplied from the PV generators to the inverters since the TEAM system makes the difference compared with the static system only for that range of input power below the power threshold of division of the generators. Hence, the TEAM design makes the difference only for the amount of time in which the power is below that limit: the longer it is, the bigger is the difference between the designs.

6.2 TEAM Design and Static Design

1. Even using a very small PV installation like the one we have been able to simulate into our laboratory we can already achieve efficiency improvements using the TEAM design compared with the static design of a PV system.
2. A cloudy day in which the power we collect from the sun is so low that the division power limit is not even reached and the generators keep supplying only one inverter is the best case to show the utility of the TEAM system because the system works all day long with only one sizing factor and only one inverter is connected.
3. During a sunny day, having only one inverter connected during the hours of the morning and of the evening in which the power is low still gives us an efficiency improvement using the TEAM design because, changing the sizing factor, again the system auto-configures itself to situations of low power injection and so increasing the efficiency of the inverter and, hence, the efficiency of the whole system.
4. We can certainly affirm that the best results come from the cloudy day experiments but this is something that we expected since the reconfiguration and, therefore, the TEAM concept is most efficient when there is low power injected into the inverters, once the inverters are separated, in fact, the system configuration of TEAM and static system is

identical and identical results are expected.
Only when the generators are connected we expect a difference.

6.3 Static versus Advanced Systems

With the same hardware we use to realize the TEAM design and with a little modification to the software of control it is possible to improve even more the gain of energy compared to the static system design.

The idea at the base of this improvement is to force the system to start working for a U_{PV_start} voltage threshold smaller than that nominal of the inverter and, this way, we are able to inject into the grid a large amount of energy otherwise left out of the conversion.

For the experiments we have made, we measured an energy total improvement, always referred to the static system design of 253kJ for the sunny curve and 466kJ for the cloudy curve. Even if these values are not very different, the difference in percentage of gain they represent is huge: 2.4% for the sunny curve while 76.2% for the cloudy one.

As earlier explained this is related to the total energy amount of energy that we are able to supply, for each curve, using the static system design.

6.4 Summary

According to the results of the chapter 5 and chapter 6 we can certainly show some hot points:

1. Passing from a static system design to the TEAM system design allows us to improve the total efficiency of the system in terms of energy injected into the grid.
2. Using the “advanced” design we manage to improve the efficiency passing from static standard to static advanced design and from TEAM standard to TEAM advanced. The hardware and software needed to realize this option is almost the same needed to realize the TEAM design so, even if there is an improvement using the advanced design on the static system it is not worth to think to use an advanced design without including also the TEAM concept. Besides the hardware needed to realize the TEAM system is already partially included into the inverters themselves since they give information about power, voltage, energy and so on. The hardware missing is made of few relays and a simple control which can be realized and integrate into the inverters themselves making the resulting total cost of the improvement hardware extremely cheap for the constructors.

3. If the PV installation is so little that one inverter is enough to convert the energy self-produced then there is no sense to buy two inverters to step to the TEAM design but usually more inverters are always necessary and if with two inverters we already achieve improvements of the efficiency, better improvements can be reached with more inverters.
4. Even if the difference in amount of energy between cloudy and sunny tests isn't that big, but it is in percentage, we might say that the best condition in which we can appreciate the TEAM concept effects is with low level irradiance.
5. Using a sunny curve, the worst case for these experiments, where the maximum power reached was below 700W we have been able to reach a total gain of 2.4% in terms of injected energy into the grid using two inverters.

The TEAM concept model foresee higher improvements when the PV installation involves more inverters and considering PV system of higher energy we believe that the TEAM design could be an interesting solution to apply designing PV installations.

6.5 Future Possible Investigations

1. During the experiments we have noticed that there are some working conditions for the inverters which were unexpected: there are some circumstances in terms or voltage and current that, if not respected, cause the inverters to restart even if they were operative till a moment before the division of the generators. It would be interesting, therefore, to verify the results we have reached within this thesis using different inverters made by SMA and inverters made from other brands.

2. The TEAM design needs an auxiliary generator for better performance because, as we said in chapter 4, we want to avoid losing eighty seconds of not injection of energy when the second inverter gets involved in the process of conversion. Besides, the auxiliary generator is also used with the TEAM advanced solution to force an earlier turn on of the first inverter. To do so we need to give input power to the inverter with a voltage level value bigger than the U_{PV_start} value.
   It would be interesting to consider a possible different solution in which, instead of using an auxiliary generator to force this earlier operative state, we use reconfigurable generators that switch from parallel connection to series connection just for the time needed to give power to the first inverter with an opportune level of voltage. This solution could be interesting because it allows us to perform the task without getting energy from the grid. This solution would be even more interesting because it implies no need of extra hardware needed to convert energy AC from the grid in energy DC to feed the inverter.

3. The curves we have been using during these experiments are characterized from a not very high maximum power level because of the limits imposed by the equipment we had. Interesting would be trying these same experiments with systems involving higher energy. This is something quite difficult to do in laboratories but it could be done realizing two parallel PV systems connected to two parallel conversion systems but with a static design one and a TEAM advanced design the other.

4. A laboratory test possible with these same curves, instruments and control, would be trying the same experiments for each case and each design a certain number of times in order to give us enough data for making a statistical characterization of the results and, finally, giving answers with a defined accuracy.

APPENDIX A – FLOWCHARTS OF CONTROL

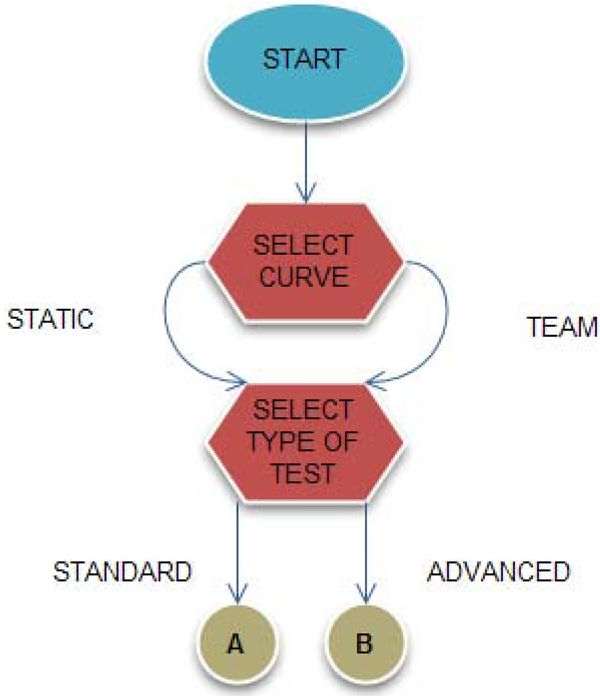

Fig. A1 Start algorithm for selection of the tests to conduct

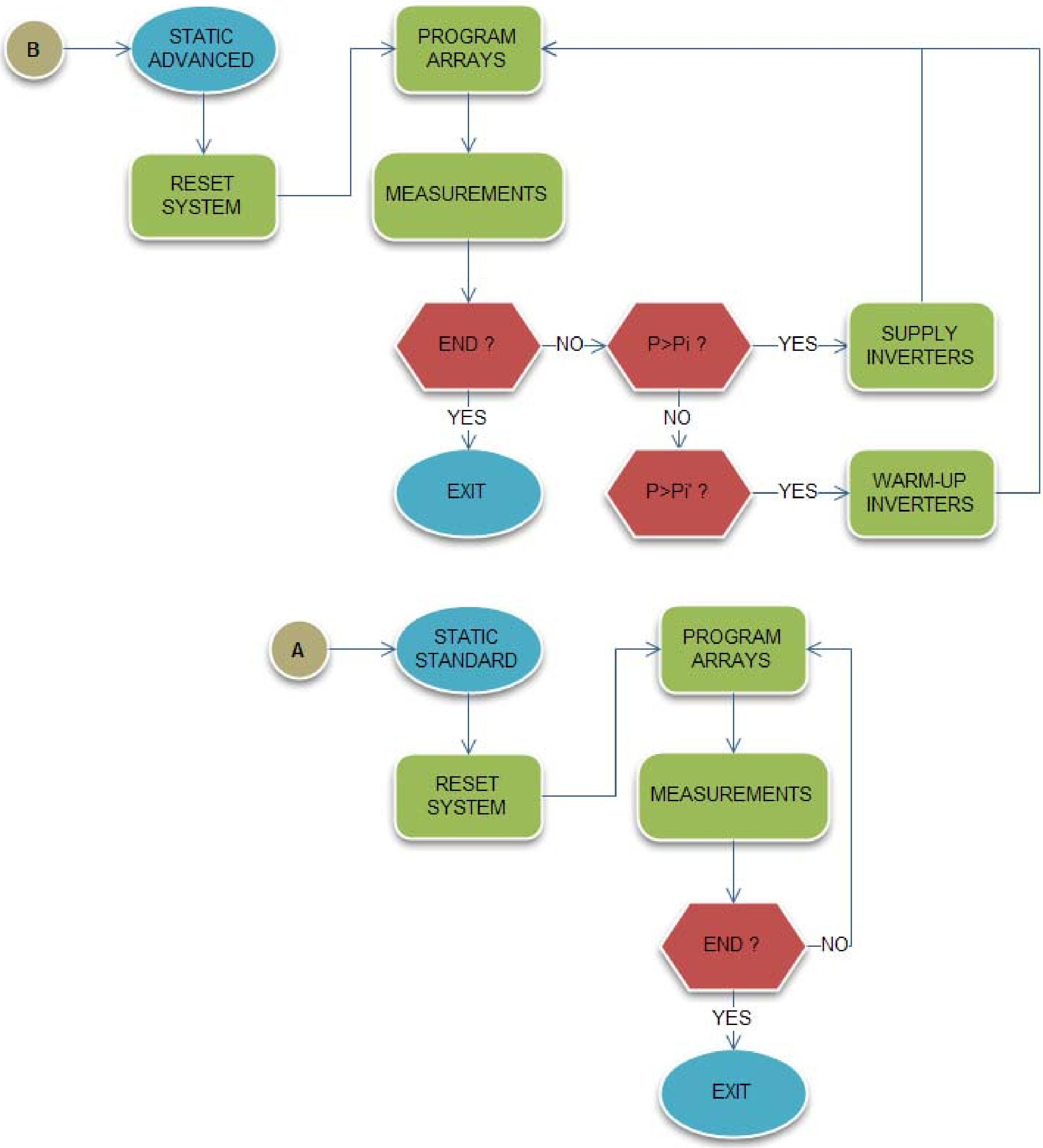

Fig. A2 Algorithm for static design advanced and standard test

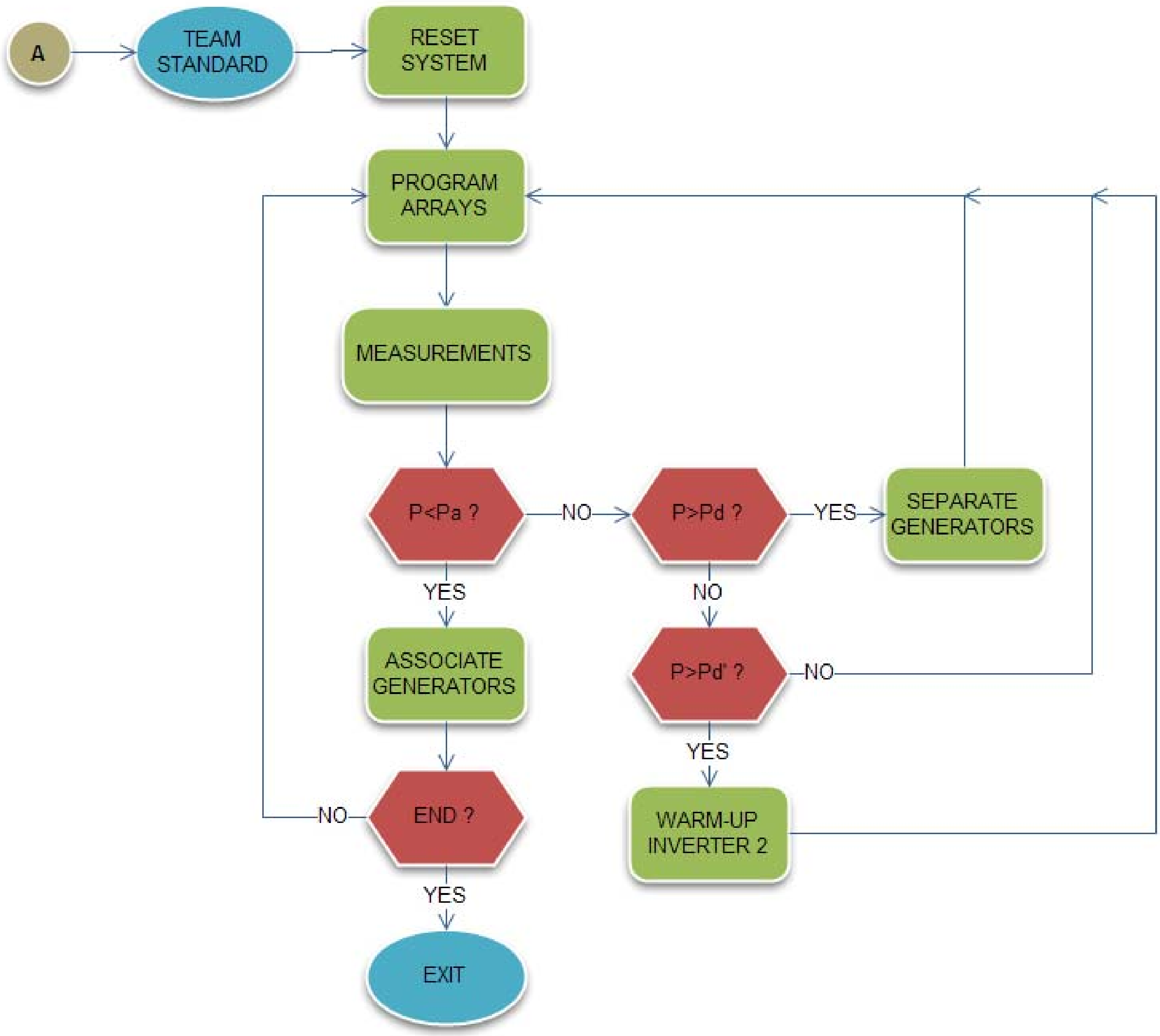

Fig. A3 Algorithm for TEAM design standard test

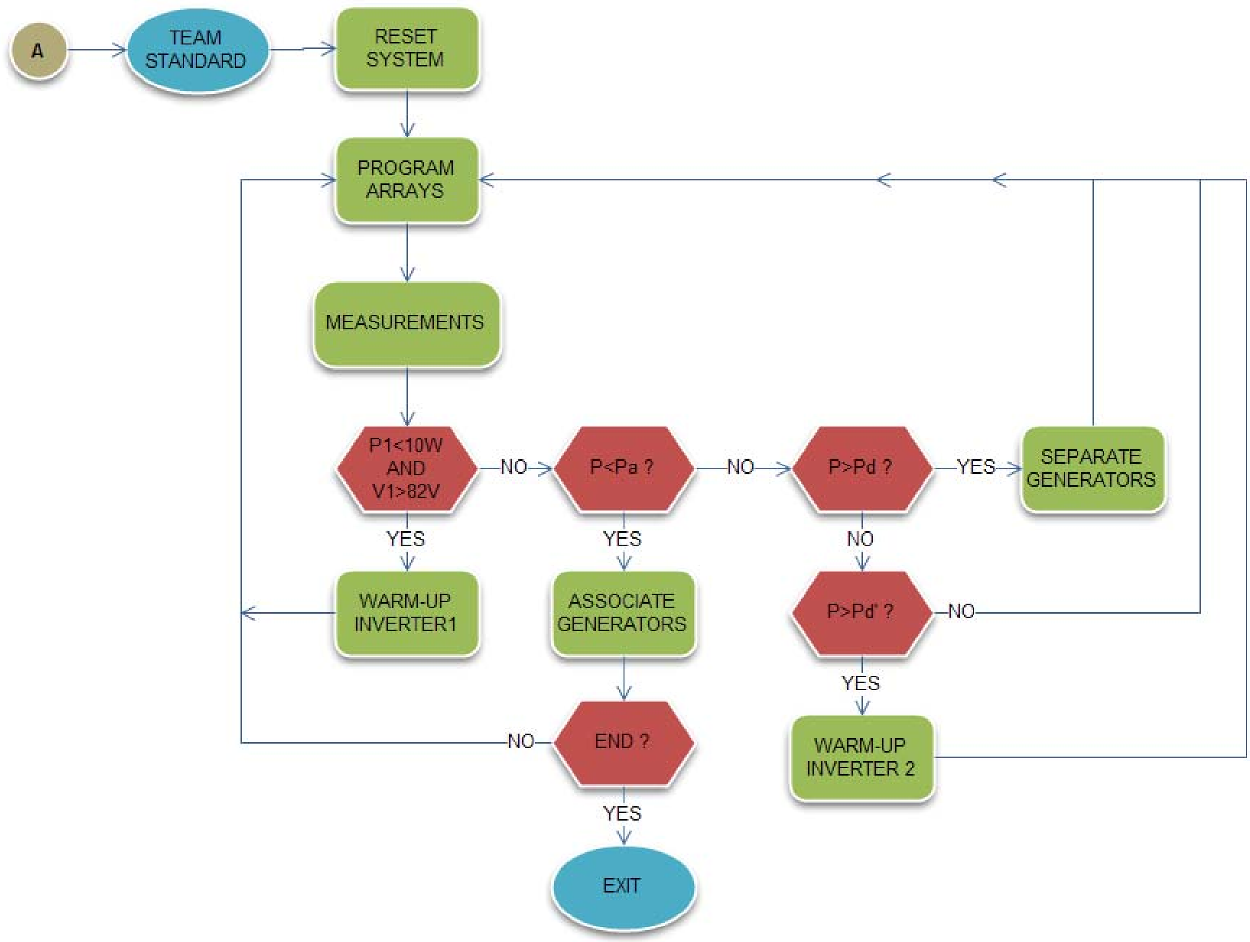

Fig. A4 Algorithm for TEAM design advanced test

APPENDIX B – MODEL OF GENERATION SYSTEM

The system of generation for a photovoltaic installation can be modelled considering the physics of solid state: the behaviour of a solar cell when working as current generator can be explained as the difference between the current photo-generated and the current of the diode: $I = I_L - I_D$.

Developing the expression for the current of the diode we arrive to the math expression with which we model the generator:

$$I = I_L - I_O\left[\exp\left(\frac{V + I \cdot R_S}{m \cdot V_T}\right) - 1\right] - \frac{V + I \cdot R_S}{R_P} \qquad \text{B.1}$$

Where:

- I_L is the photo-generated current
- I_0 is the saturation current of the diode
- R_S is the series resistance
- R_P is the parallel resistance
- m is the ideal factor of the diode
- V_T is the thermal voltage

The expression B.1 is quite simple and describes well the characteristic voltage-current of most of photovoltaic solar cells.

In cells with high quality (with high fill-factor FF and high efficiency) the parallel resistance is really big compared with the numerator of the last part of the expression B.1 and, hence, it is irrelevant compared with the rest.

Simplifying the expression we obtain:

$$I = I_L - I_O\left[\exp\left(\frac{V + I \cdot R_S}{m \cdot V_T}\right) - 1\right] \qquad \text{B.2}$$

The simplified model of Green considers the following simplification:

$\exp\left(\frac{V + I \cdot R_S}{m \cdot V_T}\right) >> 1$ and, consequently, the expression B.2 simplifies more:

$$I = I_L - I_O\left[\exp\left(\frac{V + I \cdot R_S}{m \cdot V_T}\right)\right] \qquad \text{B.3}$$

From the model we see that at V=0 I≅Isc and hence:

$$I = I_{SC} - I_O\left[\exp\left(\frac{V + I \cdot R_S}{m \cdot V_T}\right)\right] \qquad \text{B.4}$$

Moreover, at I=0 V=Voc, $I_{SC} - I_O\left[\exp\left(\frac{V_{OC}}{m \cdot V_T}\right)\right] = 0$ and consequently:

$$I = I_{SC}\left[1 - \exp\left(\frac{V - V_{OC} + I \cdot R_S}{m \cdot V_T}\right)\right] \qquad \text{B.5}$$

Since we are not working with a solar cell but with solar panels we must include in the simplified expression of Green the number of cells in series and in parallel:

$$I = I_{SC}\left[1 - \exp\left(\frac{V \cdot N_P - V_{OC} + I \cdot R_S \cdot N_S}{m \cdot V_T \cdot N_P \cdot N_S}\right)\right] \qquad \text{B.6}$$

The equation B.6 is one of the equations we will need for our calculations. The other equation comes from the relationship between Vmp, Imp and Pmax, in fact, Pmax represents the point of maximum power and it is defined by the Vmp voltage value and Imp current value.

The maximum power point is calculated through a differential equation:

$$\frac{dP}{dV} = 0 \Rightarrow \frac{d}{dV}(VI) \qquad \text{B.7}$$

Where I is given from B.6 or, said in other words, B.6 and B.7 make a mathematic system of two equations in two variables to solve and, known Vmp and Imp, we can solve the system and recover Voc and Isc.

BIBLIOGRAFY AND REFERENCES

[1] Velasco, G.: “Análisis orientado a la estimación de la eficiencia energética de los sistemas fotovoltaicos conectados a red basados en configuraciones dinámicas”.

[2] Velasco, G.; Guinjoan, F.; Pique, R.; Negroni, J.J., "Sizing Factor Considerations for Grid-Connected PV Systems Based on a Central Inverter Configuration," IEEE Industrial Electronics, IECON 2006 - 32nd Annual Conference on, pp.2718-2722, 6-10 Nov. 2006.

[3] Velasco, G.; Guinjoan, F.; Pique, R.; Negroni, J.J.; Conesa, A.: “Inverter Power Sizing Considerations in Grid-Connected PV Systems”, Electronic Engineering Department – Polytechnic University of Catalonia (UPC) CEIB-EUETIB, C/. Compte d’Urgell, 187 – ETSETB, C/. Jordi Girona, 31 Barcelona, SPAIN.

[4] Velasco, G.; Guinjoan, F.; Piqué, R.: “Energy Efficiency Improvement in Reconfigurable Grid-Connect-ed PV Systems with Adjustable Sizing Factor”, Electronic Engineering Department (EEL) – Polytechnic University of Catalonia (UPC) - CEIB-EUETIB, C/. Compte d’Urgell, 187 – ETSETB, C/. Jordi Girona, 31 Barcelona, SPAIN.

[5] Burger, B.; Rüther, R.: “Inverter sizing of grid-connected photovoltaic systems in the light of local solar resource distribution characteristics and temperature”, Fraunhofer-Institute for Solar Energy Systems ISE, Department of Electrical Energy Systems, Heidenhofstr. 2, 79110 Freiburg, Germany; LABSOLAR—Laboratorio de Energia Solar, LabEEE—Laboratorio de Eficiencia Energetica em Edificacoes, Universidade Federal de Santa Catarina/UFSC, Caixa Postal 476, Florianopolis—SC 88040-900, Brazil

[6] Green, M. A.: “Solar Cells. Operating, Principles, Technology and System Application”. University of South Wales (1986). 274pp (1986).

[7] SMA Sunny Boy / Sunny Mini Central – Operating Parameters